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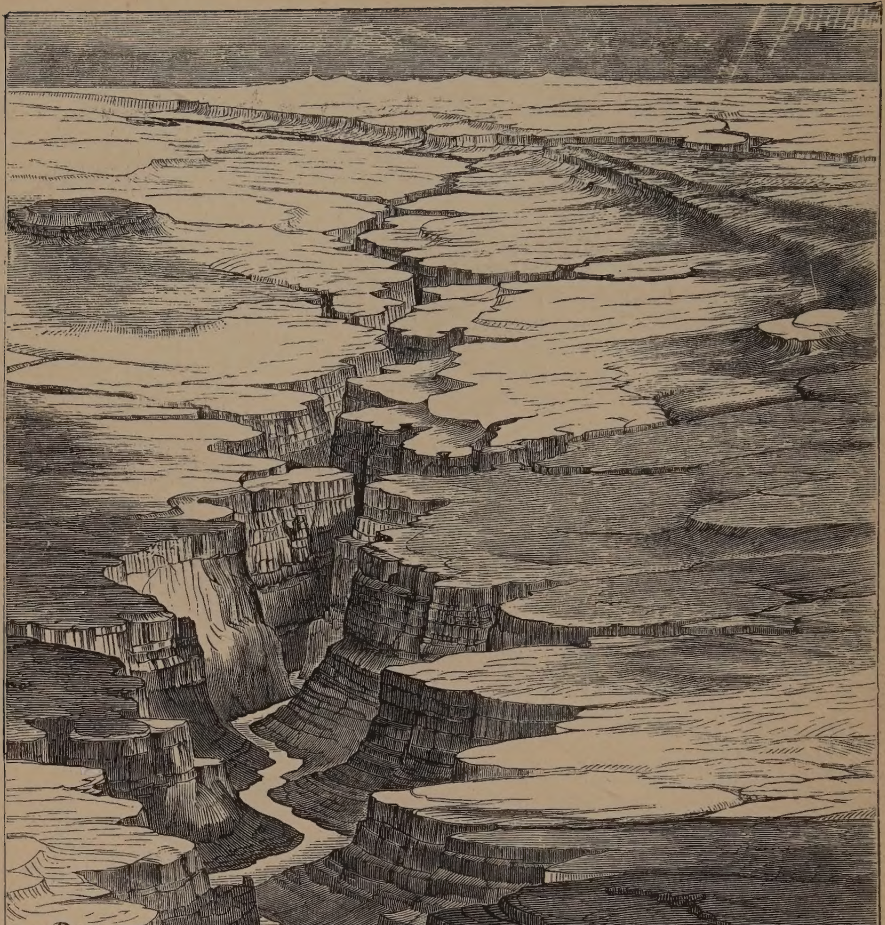

Bird's-eye View of Marble Cañon from the Vermilion Cliffs, near the Mouth of the Paria. In the distance the Colorado River is seen to turn to the west, where its gorge divides the Twin Plateaus. On the right are seen the Eastern Kaibab Displacements appearing as folds, and farther in the distance as faults.

ELEMENTS OF GEOLOGY

A TEXT-BOOK FOR COLLEGES AND FOR THE GENERAL READER

BY

JOSEPH LE CONTE

Author of Religion and Science; Sight: An Exposition of the Principles of Monocular and
Binocular Vision; Evolution in its Relation to Religious Thought, etc.;
And Professor of Geology and Natural History in the University of California

FOURTH EDITION, REVISED AND ENLARGED
WITH NEW PLATES AND ILLUSTRATIONS

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PREFACE TO THE FOURTH EDITION.

In this new edition of my Elements of Geology, while the form, and largely the matter, of the third edition are retained, the changes necessitated by the rapid advance of geological science are so numerous and important as to require a complete resetting of the whole work. I have striven, however, to keep the work within the limits necessary for a text-book. The changes have been partly by replacement, partly by modification of statement, and partly by addition of new matter. But while more than sixty new figures and many new paragraphs are introduced, yet the actual increase in the number of figures is only twenty, and of pages twenty-five.

The most important additions are a fuller discussion of the difficult subject of *earthquakes*, in the light of the recent investigations of Milne, Dutton, Seebach, and Schmidt; a brief account of the origin of *varieties of igneous rocks by differentiation of rock-magmas*, made necessary by the writings of Iddings and others; a greater emphasis on the *Cambrian* as a subdivision of the Palæozoic; the latest results of Walcott, Matthew, and Beecher on the *structure and affinities of Trilobites;* the latest results of Marsh, Cope, Osborn, Scott, and Wortman on the *structure and affinities of Mesozoic reptiles and Mesozoic and Tertiary mammals;* some clearer statement on the subject of the *causes of the glacial climate;* and a brief discussion of the *causes of geological climates* in general.

I wish to acknowledge my obligations to many American geologists for help in preparing this edition, but especially to Profs. Marsh, Beecher, and Pirsson for many valuable suggestions.

JOSEPH LE CONTE.

August 10, 1896.

PREFACE TO THE FIRST EDITION.

In preparing the following work I have not attempted to make an exhaustive *manual* to be thumbed by the special student; for, even if I felt able to write such a work, Prof. Dana's is already in the field, and is all that can be desired in this respect. I have endeavored only to present clearly to the thoroughly cultured and intelligent student and reader whatever is best and most interesting in Geological Science. I have attempted to realize what I conceive to be comprised in the word *elements*, as contradistinguished from *manual*. I have attempted to give a really scientific presentation of all the departments of the wide field of geology, at the same time avoiding too great multiplication of detail. I have desired to make a work which shall be both interesting and profitable to the intelligent general reader, and at the same time a suitable text-book for the higher classes of our colleges. In the selection of material and mode of presentation I have been guided by long experience, as to what it is possible to make interesting to a class of young men, somewhat advanced in general culture and eager for knowledge, but not expecting to become special geologists. In a word, I have tried to give such knowledge as every thoroughly cultured man ought to have, and at the same time is a suitable foundation for the further prosecution of the subject to those who so desire. The work is the substance of a course of lectures to a senior class, organized, compacted, and disencumbered of too much detail, by representation for many successive years, and now for the first time reduced to writing.

Most text-books now in use in this country are, in my opinion, either too elementary on the one hand, or else adapted as manuals for the specialists on the other. I wish to fill this gap—to supply a want felt by many intelligent students and general readers, who desire a really scientific general knowledge of geology. Lyell's Elements comes nearest to supplying this want; but there are two objections to this admirable work: 1. The principles (dynamical geology) are separated from the elements (structural and historical geology), and treated in a different work; 2. Its treatment of *American* geology is of course meager.

I have treated several subjects in dynamical and structural geology—e. g., rivers, glaciers, volcanoes, geysers, earthquakes, coral-reefs, slaty cleavage, metamorphism, mineral veins, mountain-chains, etc.—more fully than is common. I feel hopeful that many geologists and physicists will thank me for so doing. I am confident that I give somewhat fairly the present condition of science on these subjects.

In the historical part I have found much more difficulty in being scientific without being tiresome, and in being interesting without being superficial and wordy. I have attempted to accomplish this difficult task by making *evolution* the central idea, about which many of the facts are grouped. I have tried to keep this idea in view, as a thread running through the whole history, often very slender—sometimes, indeed, invisible—but reappearing from time to time to give consistency and meaning to the history.

If this work have any advantage over others already before the public, it is chiefly in the two points mentioned above, viz., in a fuller presentation of some subjects in dynamical and structural geology, and in the attempt to keep evolution in view, and to make it the central idea of the history. Another advantage, I believe, is that it does not seek to compete with the best works now before the public, but occupies a distinct field and supplies a distinct want.

I have confined myself mostly, though not entirely, to American geology, especially in giving the distribution of the rocks and the physical geography of the different periods. In only one case have I made American geology subordinate, viz., in the Jura-Trias period, and that only because of the meagerness of the record of this period in this country.

In a science so comprehensive and many-sided as geology, it is simply impossible, as every teacher knows, to avoid anticipations in one part of what strictly belongs to a subsequent part. It is for this reason that the order of presentation of the different departments, and of the various subjects under each department, is so different in the hands of different writers. The order which I have adopted I know is not free from objection on this score, but it seemed to me, on the whole, the best.

In preparing the work I have, of course, drawn largely from many sources, both text-books and works of original research; for whatever of merit there be in a work of this kind must consist not so much in the novelty of the matter as in the selecting, grouping, and presentation. Such obligations are acknowledged in the pages of the work. I can not forbear, however, making here a special acknowledgment of my indebtedness, in the historical part, to the invaluable Manual of Prof. Dana. I must also acknowledge especial indebtedness to Profs. Marsh, Newberry, and Cope, and the geologists and paleontologists of the United States Surveys, in charge of Prof. Hayden and Lieutenant Wheeler, not only for valuable materials, but also for much personal aid.

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INTRODUCTORY.

DEFINITION OF GEOLOGY, AND OF ITS DEPARTMENTS.

GEOLOGY is the physical history of the earth and its inhabitants, as recorded in its structure. It includes an account of the changes through which they have passed, the laws of these changes, and their causes. In a word, it is the *history of the evolution of the earth and its inhabitants.*

The fundamental idea of geology, as well as its principal subdivisions and its objects, may be most clearly brought out by comparing it with organic science. We may study an organism from three distinct points of view: 1. We may study its general form, the parts of which it is composed, and its minute internal structure. This is *anatomy*. It is best studied in the *dead* body. 2. We may study the *living* body in action, the function of each organ, the circulation of the fluids, and the manner in which all contribute to the complex phenomena of life. This is *physiology*. 3. We may study the living and *growing* body, by watching the process of *development* from the egg to the adult state, and striving to determine its laws. This is *embryology*.

So, looking upon the earth as an organic unit, we may study its form, the rocks and minerals of which it is composed, and the manner in which these are arranged; in other words, its external form and internal structure. This is the anatomy of the earth, and is called *structural geology*. Or, we may study the earth under the action of physical and chemical forces, the action and reaction of land and water, of earth and air, and the effects of these upon the form and structure. This is the physiology of the earth, and is called *dynamical geology*. Finally, we may study the earth in the progress of its development, from the earliest chaotic condition to its present condition as the abode of man, and attempt to determine the laws of this development. This is the embryology of the earth, or *historical geology*.

Principal Departments.—The science of geology, therefore, naturally divides itself into three parts, viz.: 1. *Structural geology*, or geognosy. 2. *Dynamical geology*, or physical and chemical geology. 3. *Historical geology*, or the history of the earth.

But there are two important points of difference between geology and organic science. The central department of organic science is physiology, and both anatomy and embryology are chiefly studied to throw light on this. But the central department of geology, to which the others are subservient, is history. Again: in case of organisms—especially animal organisms—the nature of the changes producing development is such that the record of each previous condition is successively and entirely obliterated; so that the science of embryology is possible only by direct observation of each successive stage. If this were true also of the earth, a history of the earth would, of course, be impossible. But, fortunately, we find that each previous condition of the earth has left its record indelibly impressed on its structure.

Order of Treatment.—The prime object of geology is to determine the history of the earth, and of the organisms which have successively inhabited its surface. The structure and constitution of the earth are the *materials* of this history, and the physical and chemical changes now going on around us are the means of interpreting this structure and constitution. Evidently, therefore, the only logical order of presenting the facts of geology is to study, first, the causes, physical and chemical, *now* in operation and producing structure; then the structure and constitution of the earth which, *from the beginning*, have been produced by similar causes; and, lastly, from the two preceding to unfold the history of the earth.

Geology may be defined, therefore, as *the history of the earth and its inhabitants, as revealed in its structure, and as interpreted by causes still in operation.**

There is no other science which requires for its full comprehension a general knowledge of so many other departments of science. A knowledge of mathematics, physics, and chemistry, is required to understand dynamical geology; a knowledge of mineralogy and lithology is required to understand structural geology; and a knowledge of zoölogy and botany is required to understand the affinities of the animals and plants which have successively inhabited the earth, and the laws which have controlled their distribution in *time.*

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* The great importance of studying "causes now in operation" as a basis of scientific geology was first brought out by Hutton, but it was through the writings of Sir Charles Lyell that it became generally accepted.

PART I.

DYNAMICAL GEOLOGY.

The agencies now in operation, modifying the structure of the surface of the earth, may be classed under four heads, viz., *atmospheric agencies*, *aqueous agencies*, *igneous agencies*, and *organic agencies.* These agencies have operated from the beginning, and are still in operation. We study their operation *now*, in order that we may understand their *effects* in previous epochs of the earth's history—i. e., the structure of the earth.

While all geologists agree that the *nature* of the agencies which have operated in modifying the earth's surface has remained the same from the beginning, they differ in their views as to the *energy* of their operation in different periods. Some believe that their energy has been much the same throughout the whole history of the earth, while others believe that many facts in the structure of the earth require much greater operative energy than now exists. We will attempt to show hereafter that neither of these extreme opinions is probably true, but that some of these agencies have been *decreasing*, while others have been *increasing*, with the progress of time. It is the constant change of balance between these which determines the development of the earth.

CHAPTER I.

ATMOSPHERIC AGENCIES.

The general effect of atmospheric agencies is the disintegration of rocks and the formation of soils. The atmosphere is composed of nitrogen and oxygen, with small quantities of watery vapor and of carbonic acid. There are but few rocks which are not gradually disintegrated under the constant chemical action of the atmosphere. The chemical agents of these changes are oxygen, carbonic acid, and watery vapor, the nitrogen being inert. To these must be added, where vegetation is present, the products of vegetable decomposition, especially ammonia *and humus acids.*[*]

Atmospheric agencies graduate so insensibly into aqueous agencies that it is difficult to define their limits. Water, holding in solution carbonic acid and oxygen, may exist as invisible vapor; or, partially condensed as fogs; or, completely condensed, as rain falling upon and percolating the earth. In all these forms its chemical action is the same, and, therefore, can not be separated and treated under different classes; and yet the same rain runs off from and erodes the surface of the earth, comes out from the strata and forms springs, rivers, etc., all of which naturally fall under aqueous agencies. We shall, therefore, treat of the *chemical* effects of atmospheric water in the *disintegration* of rocks, and *the formation of soils*, under the head of atmospheric agencies; and the *mechanical* effects of the same, in *eroding* the surface and *carrying away* the soil thus formed, under the head of aqueous agencies. In moist climates vegetation clothes and protects soil from erosion, but favors decomposition of rocks and formation of soil.

Atmospheric agencies are obscure in their operation, and, therefore, imperfectly understood. Yet these are not less important than aqueous agencies, since they are the necessary condition of the operation of the latter Unless rocks were first disintegrated into soils by the action of the atmosphere, they would not be carried away and deposited as sediments by the agency of water. These two agencies are, therefore, of equal power and importance in geology, but they differ very much in the conspicuousness of their effects. Atmospheric agencies act almost equally at *all times* and at *all places*, and their effects, at any one place or time, are almost imperceptible. Aqueous agencies, on the contrary, in their operation are *occasional*, and to a great extent *local*, and their effects are, therefore, more striking and easily studied. Nevertheless, the aggregate effects of the former are equal to those of the latter.

Soils.—All soils (with the trifling exception of the thin stratum of vegetable mold which covers the ground in certain localities) are formed from the disintegration of rocks. Sometimes the soil is formed *in situ*, and, therefore, rests on its parent rock. Sometimes it is removed as fast as formed, and deposited at a distance more or less remote from the parent rock. The evidence of this origin of soils is clearest when the soil is formed *in situ*. In such cases it is often easy to trace every stage of gradation between perfect rock and perfect soil. This is well seen in railroad cuttings, and in wells in the gneissic or so-called *primary* region of our southern Atlantic slope. On examining such a section, we find near the surface perfect soil, generally red clay; beneath this we find the same material, but lighter colored, coarser, and more distinctly stratified; beneath this, but shading into it by imperceptible gradations, we have what seems to be stratified rock, but it crumbles into coarse dust in the hand; this passes by imperceptible gradations into rotten rock, and finally into perfect rock. There can be no doubt that these are all different stages of a gradual decomposition. But closer observation will make the proof still clearer. In gneissic and other metamorphic regions it is not uncommon to find the rock traversed, in various directions, by veins of quartz or *flint.* Now, in sections such as those mentioned above, it is common to find such a quartz-vein running through the rock and upward through the superincumbent soil, until it emerges on the surface. In the slow decomposition of the rock into soil, the quartz-vein has remained unchanged, because quartz is not affected by atmospheric agencies. Chemical analysis, also, always shows an evident relation between the soil and the subjacent or country rock, except in cases in which the soil has been brought from a considerable distance.

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[*] Alexis Julien, Proceedings of the American Association for the Advancement of Science, vol. xxviii, p. 311 *et seq.*

The *depth* to which soil will thus accumulate depends partly on the nature of the rock and the rapidity of decomposition, partly on the slope of the ground, and partly on climate. In Brazil, undisturbed soils are found three hundred feet deep.[*] When the slope is considerable, as at *d* (Fig. 1), the rocks are bare, not because no soil is formed, but because it is removed as fast as formed; while at *a* the soil is deep, being formed partly by decomposition of rock *in situ*, and partly of soil brought down from *d*. Wherever perfect soil is found resting on sound rock, the soil has been shifted.

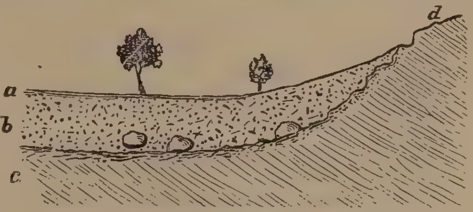

FIG. 1.—Ideal Section, showing Rock passing into Soil.

If rocks were solid and impervious to water, this process would be almost inconceivably slow; but we find that all rocks, for reasons to be discussed hereafter, are broken by fissures into irregular prismatic blocks, so that a perpendicular cliff of rock usually presents the appearance of rude gigantic masonry. These fissures, or *joints*, increase immensely the surface exposed to the action of atmospheric water. Again, on closer inspection, we find even the most solid parts of rocks, i. e., the blocks themselves, penetrated with *capillary fissures* which allow water to reach every part. Thus the rock is decomposed, or *becomes rotten*, to a great depth below the surface. But, while the rock is gradually

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[*] American Journal of Science, 1884, vol. xxvii, p. 130.

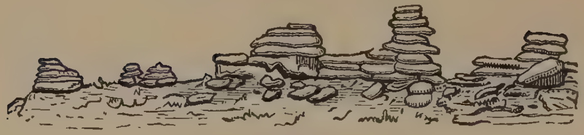

FIG. 2.

changed into soil, the soil is also slowly carried away by agencies to be hereafter considered; and these changes, taking place more rapidly in some places than in others, give rise to a great variety of forms, some of which are represented in the accompanying figure (Fig. 2).

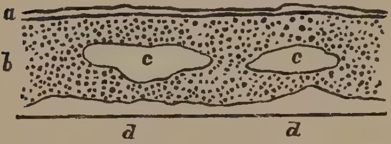

FIG. 3.—*a*, vegetal soil; *b*, mineral soil; *c*, harder portions of rock left in process of disintegration; *d*, underlying rock.

In the process of disintegration the original blocks lose their prismatic form, and become more or less rounded, and are then called *bowlders of disintegration.* These may lie on the surface (Fig. 2), or may be buried in the soil (Fig. 3). When of great size and very solid, so as to resist decomposition to a greater extent than the surrounding rocks, they often form huge *rocking-stones* (Fig. 4). These must not be confounded with true bowlders and rocking-stones which are brought from a distance, by agencies which we will discuss hereafter, and which are, therefore, entirely different from the subjacent or country rock.

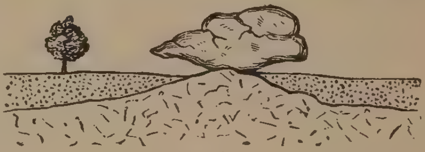

FIG. 4.

General Explanation.—The process of rock-disintegration may be explained, in a general way, as follows: Almost all rocks are composed partly of insoluble materials, and partly of materials which are slowly dissolved by atmospheric water. In the process of time, therefore, these latter are dissolved out, and the rock crumbles into an insoluble dust, more or less saturated with water holding in solution the soluble ingredients. To illustrate: common hardened mortar may be regarded as artificial stone; it consists of carbonate of lime and sand; the carbonate of lime is soluble in water containing carbonic acid (atmospheric water), while the sand is quite insoluble. If, therefore, such mortar be exposed to the air, it eventually crumbles into sand, moistened with water containing lime in solution. Again, to take a case which often occurs in Nature, it is not uncommon to find rock through which iron pyrites, FeS_2, is abundantly disseminated. This mineral is insoluble; but under the influence of water containing oxygen (atmospheric water) it is slowly oxidized and changed into *sulphate* of iron, or *copperas*, which, being soluble, is washed out, and the rock crumbles into an insoluble dust or soil, saturated with a solution of the iron salt. We have given these only as illustrative examples. We now proceed to give examples of the principal kinds of rocks, and of the soils formed by their disintegration.

Granite, Gneiss, Volcanic Rocks, etc.—Granite and gneiss are mainly composed of three minerals, *quartz*, *feldspar*, and *mica*, aggregated together into a coherent mass. Quartz is unchangeable and insoluble in atmospheric water. Mica is also very slowly affected. Feldspar is, therefore, the decomposable ingredient. But feldspar is, itself, a complex substance, partly soluble and partly insoluble. It is essentially a silicate of alumina, united with a silicate of potash or soda, although it often contains also small quantities of iron and lime. Now, while the silicate of alumina is perfectly insoluble, the other silicates are slowly dissolved by atmospheric water, with the formation of carbonates, and the silicate of alumina is left as *kaolin or clay*. But, since we may regard the original rock as made up of quartz and mica, bound together by a cement of feldspar, the disintegration of the latter causes the whole rock to lose its coherence, and the final result of the process is a mass of clay containing grains of sand and scales of mica, and moistened with water containing a potash salt. If there be any iron in the feldspar, or if there be other decomposable ingredients in the rock containing iron, such, for example, as hornblende, the clay will be red. This is precisely the nature of the soil in all our primary regions. *Volcanic rocks* decompose into clay-soils often, though not always, deeply colored with iron.

Limestone.—Pure limestone may be regarded as composed of granules of carbonate of lime, cohering by a cement of the same. The dissolving of the cement by atmospheric water forms a lime-soil, moistened with a solution of carbonate of lime (hard water). Impure limestone is a carbonate of lime, more or less mixed with sand or clay; by disintegration it forms, therefore, a *marly soil.*

Sandstones.—Sandstones consist of grains of sand cemented together by carbonate of lime or peroxide of iron. Where peroxide of iron is the cementing substance, the rock is almost indestructible, since this substance is not changed by atmospheric water: hence the great value of red sandstone as a building-material. But, when carbonate of lime is the cementing material, this substance, being soluble in atmospheric water, is easily washed out, and the rock rapidly disintegrates into a sandy soil.

Slate.—In a similar manner *slate-rocks* disintegrate into a pure clay soil by the solution of their cementing material, which is often a small quantity of carbonate of lime.

There can be no doubt that all soils are formed in the manner above indicated. We have given examples of soils formed *in situ*, but, as soils are often shifted, they are usually composed of a mixture formed by the disintegration of several kinds of rock. In some cases the soil has been formed *in situ* during the present geological epoch, and the process is still going on before our eyes. Such are the soils of the hills of the up-country or primary region of our Southern Atlantic States.* Sometimes the soil formed in the same way has been shifted to a greater or less distance. Such are the soils of our valleys and river-bottoms. In still other cases the soil has been formed by the process already described, and transported during some previous geological epoch and not reconsolidated. Such are many of the soils of the Southern low-country or tertiary region.

MECHANICAL AGENCIES OF THE ATMOSPHERE.

Frost.—Water, penetrating rocks and freezing, breaks off huge fragments: these by a similar process are again broken and rebroken until the rock is reduced to dust. These effects are most conspicuous in cold climates and in mountain-regions. In cold climates huge piles of bowlders and earth are always seen at the base of steep cliffs (Fig. 5). Such a pile of materials, the ruins of the cliff above, is called a *talus*. In mountainous regions frost is a powerful agent in disintegrating the rocks, and in determining the outlines of mountain-peaks. This is well seen in the Alps and in the Sierra.

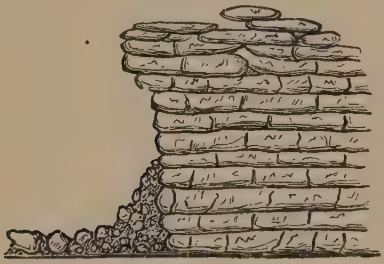
FIG. 5.

Winds.—The effect of winds is seen in the phenomenon of shifting sands. At Cape Cod, for instance, the sands thrown ashore by the sea are driven by the winds inland, and thus advance upon the cultivated lands, burying them and destroying their fertility. The sands from the beach on the Pacific coast near San Francisco are driven inland in a similar manner, and are now regularly encroaching upon the better soil. Large areas of the fertile alluvial soil of Egypt, together with their cities and monuments, have been buried by the encroachments of the Sahara Desert. The same phenomena are observed on various parts of the coast of France, Holland, and England. The rate of advance has been measured in some instances. Thus on the coast of Suffolk it is said to advance at the rate of about five miles a century; at Cape Finisterre, according to Ansted, at the rate of thirty-two miles per century, or five hundred and sixty yards per annum. The Dunes of England and Scotland are such barrens of drifting sand. Hills may be formed in this manner thirty to forty feet in height. In the nearly rainless regions of the interior of our continent, high winds, laden with sand and gravel, are a powerful agent in sculpturing the rocks into the fantastic forms so often found there.* In such regions, also, extensive deposits of wind-borne particles are sometimes found. This is especially true in the interior of Asia and in China, where, according to Richthofen, such deposits are hundreds of feet in thickness and cover thousands of square miles. Such deposits are called *Loess*. The geological importance of dust-deposits has only recently been appreciated.

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* In the Northern States, in the region of the Drift, nearly all the soil has been shifted.

CHAPTER II.

AQUEOUS AGENCIES.

The agencies of water are either *mechanical* or *chemical*. The mechanical agencies of water may be treated under the threefold aspect of *erosion*, *transportation*, and *sedimentary deposits*. We will consider them under the heads of *Rivers*, *Oceans*, and *Ice*. Under chemical agencies we will consider the phenomena of chemical deposits in *Springs* and *Lakes*.

Aqueous agencies.	Mechanical.	Rivers.......	Erosion,	Transportation,	Deposit.
		Ocean.......	“	“	“
		Ice..........	“	“	“
	Chemical.	Effects of underground water.			
		Springs......	Deposit	in.	
		Lakes	“	“	

Section 1.—Rivers.

Under the head of river agencies we include all the effects of circulating meteoric water from the time it falls as rain until it reaches the ocean: i. e., all the effects of *Rain and Rivers*.

Water, in the form of vapor, fogs, or rain, percolating through the earth, slowly disintegrates the hardest rocks. Much of these percolating waters, after accomplishing the work of soil-making, already treated in the preceding chapter, reappears on the surface in the form of springs, and gives rise to *streamlets*. A large portion of rain-water, however, never soaks into the earth, but runs off the surface, forming *rills*, which by erosion produce *furrows*. The uniting rills form *rivulets*, which excavate *gullies*. The rivulets, uniting with one another and with the streamlets issuing from springs, form *torrents*, which in their course excavate *ravines*, *gorges*, and *cañons*. The uniting torrents, finally issuing from their mountain-home upon the plains, form *great rivers*, which deposit their freight partly in their course and partly in the sea. Such is a condensed history of rain-water on its way to the ocean whence it came. Our object is to study this history in more detail.

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* Gilbert, U. S. Geographical Surveys—Lieutenant Wheeler in charge, vol. iii, Geology p. 82.

Erosion of Rain and Rivers.

The whole amount of water falling on any land-surface may be divided into three parts: 1. That which rushes immediately off the surface, and causes the floods of the rivers, especially the smaller streams; 2. That which sinks into the earth, and, after doing its chemical work of soil-making, reappears as springs, and forms the regular supply of streams and rivers; and, 3. That which reaches the sea wholly by subterranean channels. Of these, the first two are the grand erosive agents, and these only concern us at present. Of these, the former predominate in proportion as the land-surface is bare; the latter in proportion as it is covered with vegetation.

Hydrographical Basin.—An hydrographical basin of a river, lake, or gulf, is the whole area of land the rainfall of which drains into that river, lake, or gulf. Thus the hydrographical basin of the Mississippi River is the whole area drained by that river It is bounded on the east and west by the Alleghany and Rocky Mountains, and on the north by a low ridge running from Lake Superior westward. The whole area of continents, with the exception of rainless deserts, may be regarded as made up of hydrographical basins. The ridge which separates contiguous basins is called a *water-shed.* It is evident that every portion of the land, with the exception of the rainless tracts already mentioned, is subject to the erosive agency of water, and is being worn away and carried into the sea. There have been various attempts to estimate the *rate of this general erosion.*

Rate of Erosion of Continents.—This is usually estimated as follows: Some great river, such as the Mississippi, is taken as the subject of experiment. By accurate measurement *during every portion of the year,* the average amount of water discharged into the sea per second, per hour, per day, per year, is determined. This is a matter of no small difficulty, as it involves the previous determination of the average cross-section of the river and the average velocity of the current. The average cross-section × average velocity = the average discharge per second: from which may be easily obtained the annual discharge. Next, by experiment during every month of the year, the average quantity of mud contained in a given quantity of water is also determined. By an easy calculation this gives us the annual discharge of mud, or the whole quantity of insoluble matter removed from the hydrographical basin in one year. This amount, divided by the area of the river-basin, will give the average *thickness of the layer of insoluble matter removed from the* *basin in one year.* To this must be added the soluble matters, which are about one sixth as much as the insoluble.

Estimates of this kind have been made for two great rivers, viz., the Ganges and the Mississippi. The whole amount of sediment annually carried to the sea by the Ganges has been estimated as 6,368,000,000 cubic feet. This amount, spread over the whole basin of the Ganges (400,000 square miles), would make a layer $\frac{1}{1751}$ of a foot thick. The Ganges, therefore, erodes its basin one foot in 1,751 years.* The area of the Mississippi basin is 1,244,000 square miles. The annual discharge of sediment, according to the recent and accurate experiments of Humphreys and Abbot, is 7,471,411,200 cubic feet, a mass sufficient to cover an area of one square mile, 268 feet deep.† This spread over the whole basin would cover it $\frac{1}{4640}$ of a foot. Therefore, this river removes from its basin a thickness of one foot in 4,640 years. The cause of the great difference in favor of the Ganges is, that this river is situated in a country subject to very great annual fall of water, the whole of which falls during a rainy season of six months. The rains are therefore very heavy, and the floods and consequent erosion proportionately great. The erosive power of this river is still further increased by the great slope of the basin, as it takes its rise in the Himalaya, the highest mountains in the world.

Now, since continents may be regarded as made up of hydrographical basins, the average rate of their erosion may be determined either by making similar experiments on all the rivers of the world, or, since this is impracticable, by taking some river as an average. We believe the Mississippi is much nearer an average river than the Ganges. It can hardly be less than the average, for a considerable portion of the earth—as rainless deserts—is not subject to any erosion. It is probable, therefore, that the whole surface of continents is *eroded at a rate not exceeding one foot in* 4,640 *years.* For convenience we will call it one foot in 5,000 years. We will use this estimate when we come to speak of the actual erosion which has occurred in geological times.

Law of Variation of Erosive Power.—The *erosive power* of water, or its *power of overcoming cohesion, varies as the square of the velocity of the current* ($p \propto v^2$). The *velocity* depends upon the slope of the bed, the depth of the water, and many other circumstances, so numerous and complicated that it has been found impossible to reduce it to any simple law. The angle of slope, however, is evidently the most important circumstance which controls velocity, and therefore erosive power. In the upper portions of great rivers, like the Mississippi, the erosion is very great; while in the plains near the mouth there may be no erosion, but, on the contrary, sedimentary deposit. The high lands, therefore, especially mountain-chains, are the great theatres of erosion. Pure water, however, erodes very slowly, the main agents of erosion being the gravel and sand carried along by the current. The *general* effect of erosion is *leveling*. If unopposed, the final effect would be to cut down all lands to the level of the sea, at an average rate of about one foot in five thousand years. But the immediate *local* effect is to increase the inequalities of land-surface, deepening the furrows, gullies, and gorges, and increasing the intervening ridges and peaks up to a certain limit, after which it again decreases. The effect, therefore, is like that of a graver's tool, constantly cutting at every elevation, but making trenches at every stroke, although the final effect is to bring all to one level.

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* Philosophical Magazine, vol. v, p. 261.

† Humphreys and Abbot, Report on Mississippi River, pp. 148–150.

Thus land-surfaces everywhere, especially in mountain-regions, are cut away by a process of sculpturing, and the *débris* carried to the lowlands and to the sea. The smaller lines and more delicate touches are due to *rain*, the deeper trenches or heavier chiselings to rivers proper. The effects of the former are more *general* and far *greater* in the aggregate, but the effects of the latter are far more conspicuous. It is only under certain conditions that rain-sculpture becomes conspicuous. These conditions seem to be a bare soil and absence of frost. Beautiful examples are found in the arid regions of southern Utah.

We now proceed to discuss the more conspicuous effects of water concentrated in river-channels.

Examples of Great Erosion now going on: Waterfalls.

The erosive power of water is most easily studied in ravines, gorges, cañons, and especially in great waterfalls. One of the most interesting of these is Niagara.

Niagara: General Description.—The plateau on which stands Lake Erie (*P N*, Fig. 6) is elevated about three hundred feet above that of Lake Ontario, and is terminated abruptly by an escarpment about three hundred feet high (*P*). From this point a narrow gorge with nearly perpendicular sides, and two hundred to three hundred feet deep, runs backward through the higher or Erie plateau as far as the falls (*N*). The Niagara River runs out of Lake Erie and upon the Erie plateau as far as the falls, then pitches a hundred and sixty-seven feet perpendicularly, and then runs in the gorge for seven miles to Queenstown (*Q*), where it emerges on the Ontario plateau. Long observation has proved

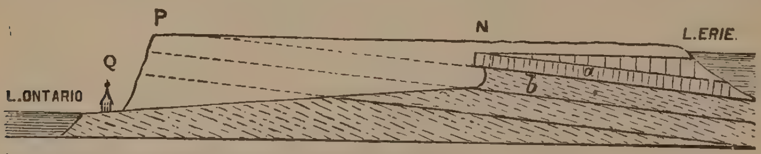

Fig. 6.—Ideal Longitudinal Section through Niagara River from Lake Erie to Lake Ontario.

that the position of the fall is not stationary, but slowly recedes at a rate which has been variously estimated at from three to five feet per annum. The process of recession has been carefully observed, and the reason why it maintains its perpendicularity is very clear. The surface-rock of Erie plateau is a firm limestone (*a*). Beneath this is a softer shale (*b*). This softer rock is rapidly eroded by the force of the falling water, and leaves the harder limestone projecting as *table-rocks.* From time to time these projecting tables are loosened and fall into the chasm below. This process is facilitated by the joint structure spoken of on page 5.

Recession of the Falls.—Now, there is every reason to believe that the fall was originally situated at Queenstown, the river falling over the escarpment at that place, and that it has worked its way backward seven miles to its present position by the process we have just described. These reasons are as follows: 1. The general configuration of the country as already described forcibly suggests such an explanation to the most casual observer. 2. A closer examination confirms it by showing that the gorge is truly *a valley of erosion*, since the strata on the two sides correspond accurately (see Fig. 7). 3. As already seen, the falls have receded in historic times at a rate of from one foot to three feet a year. The portion of the gorge thus formed under our eyes does not differ in any essential respect from other portions farther down the stream. The evidence thus far is not perfectly conclusive that the gorge was formed by the *present river* during the *present geologic epoch*, since the gorge may have been eroded during a previous epoch, and the present river found it, appropriated it as its channel, and continued to extend it. But (4) certain stratified deposits have been found by Mr. Lyell and others on the upper margin of the ravine, containing shells, all of which are identical with the shells now living in Niagara River. On the margins of all rivers we find stratified deposits of mud and sand containing dead shell. The stratified deposits found by Mr. Lyell were such mud-banks of the Niagara River before the falls had receded so far, and therefore when the river still ran on the Erie plateau at this point.

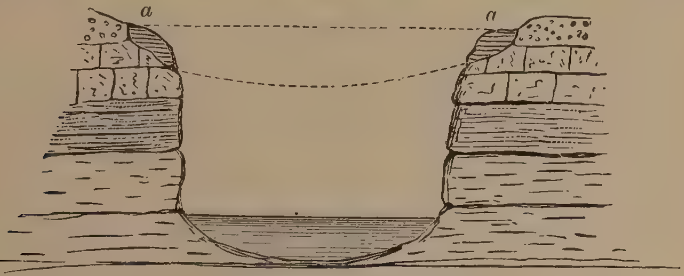

FIG. 7.—Ideal Section across Chasm below the Falls.

This is well seen in the subjoined figure, representing an ideal cross-section of the gorge below the falls. The dotted lines represent the former bed and level of the river; *a a* represent the banks of stratified mud left on the margin of the gorge, as the river eroded its bed down to its present level.

Other Falls.—The evidence is completed by examination of other great falls. In almost all perpendicular falls we find a similar arrangement of strata followed by similar results. The Falls of St. Anthony, in the Mississippi River, are a very beautiful illustration. Here we find a configuration of surface very similar to that in the neighborhood of Niagara. Above the falls the Mississippi River runs on a plateau which terminates abruptly at the mouth of Minnesota River by an escarpment about a hundred feet high. From this escarpment, backward through the upper plateau, runs a gorge with perpendicular sides nearly a hundred feet high for eight miles to the foot of the falls. The river above the falls runs on a hard, silurian limestone rock, only a few feet in thickness. Beneath this is a white sandstone, so soft that it can be easily excavated with the fingers. This sandstone forms the walls of the gorge as far as the escarpment. The recession of the falls by the undermining and falling of the limestone is even more evident than at Niagara. Tributaries running into the Mississippi just below the falls are, of course, precipitated over the margin of the gorge. Here, therefore, the same conditions are repeated, and hence are formed subordinate gorges, headed by perpendicular falls. Such are the falls and gorge of Minnehaha River, which runs into the Mississippi about two miles above the mouth of the Minnesota River.

Another admirable illustration of the conditions under which perpendicular falls recede is found in the falls of the numerous tributaries of Columbia River where the great river breaks through the Cascade Range. The Columbia River gorge is 2,500 to 3,000 feet deep. The walls consist of columnar basalt underlaid near the water-level by a softer conglomerate. Every tributary at this point emerges from a deep gorge, headed two or three miles back by a perpendicular wall, over which is precipitated the water of the tributary as a fall 200 to 300 feet high. The falling water erodes the softer conglomerate, undermines the vertical-columned basalt, which tumbles into the stream and is carried away; and thus the fall has worked back in each case about two or three miles to its present position.* All of this has taken place during the present geological epoch.†

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* Gilbert has shown (American Journal, August, 1876) that comparative freedom from detritus is another condition of the formation of perpendicular waterfalls. In muddy rivers commencing inequalities are filled up by sediment, and waterfalls can not be formed.

† American Journal of Science and Art, 1874, vol. vii, pp. 167, 259.

The wonderful falls of the Yosemite Valley, of which there are six in a radius of five miles, one of them 1,600 feet, three 500 to 700 feet, and two 300 to 400 feet high, seem to be an exception to the law given above. Their perpendicularity seems to be the result of the *comparative recency* of the evacuation of the valley by an ancient glacier, and therefore the shortness of the time during which the rivers have been falling, combined with the hardness of the granite rocks. The Yosemite gorge was not made by the present rivers during the present epoch.

Time necessary to excavate Niagara Gorge.—All attempts to estimate *accurately* the time consumed in excavating Niagara gorge must be unreliable, since we do not yet know the circumstances which controlled the rate of recession at different stages of its progress. Among these circumstances, the most important are the volume of water, and especially the hardness of the rocks, and the manner in which hard and soft are superposed. The present position of the falls is apparently favorable for rapid recession. Mr. Lyell thinks, from personal observation, that the average rate could not have been more than one foot per annum, and probably much less. At this rate it would require about 36,000 years. More recent estimates make the probable rate three feet a year, and the time, therefore, 12,000 years.* But whether we adopt the one or the other estimate, this time must not be confounded with the age of the earth. The work of excavating the Niagara chasm belongs to the present epoch, and the time is absolutely insignificant in comparison with the inconceivable ages of which we will speak in the subsequent parts of this work. The Falls of St. Anthony recedes about five feet per annum, and has made its gorge in about 8,000 years (Winchell).

Ravines, Gorges, Cañons.—We have already seen (page 12) that ravines, gorges, etc., are everywhere produced in mountain-regions by the regular operation of erosive agents. Nowhere are examples more abundant or more conspicuous than in our own country, and especially in the Western portion. On the Pacific slope, the most remarkable are the gorges of the *Fraser* and of the *Columbia* Rivers, fifty miles long and several thousand feet deep; those of the North and South Forks of the *American* River, 2,000 to 3,000 feet deep in solid slate; the cañon of the *Tuolumne* River, with its *Hetchhetchy* Valley; the cañon of the *Merced*, with its *Yosemite* Valley, with nearly vertical granite cliffs, 3,000 to nearly 5,000 feet high; and, deepest of all, the *grand cañon of King's* River, 3,000 to 7,000 feet deep, in hard granite.

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* It ought to be remembered, too, that it is probable that at one time the waters of the three upper lakes *did not drain* into Lake Erie—i. e., did not go over Niagara Falls. —Spencer, American Journal, 48, 455, 1894.

Some of these great cañons have been forming ever since the formation of the Sierra Range—i. e., since the Jurassic period. It is possible, also, that in some of them the erosive agents have been *assisted* by antecedent igneous agencies, producing fissures, which have been enlarged and deepened by water and by ice. But there are some, at least, which may be proved to have been produced wholly by erosion, and that during the present or at least during very recent geological times. We refer especially to those which have been cut through lava-streams.

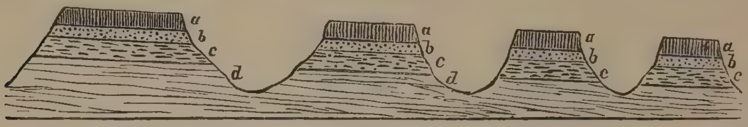

FIG. 8.—Lava-Stream cut through by Rivers: *a a*, Basalt; *b b*, Volcanic Ashes; *c c*, Tertiary; *d d*, Cretaceous Rocks. (From Whitney.)

In Middle and Northern California are found lava-streams which have flowed from the crest of the Sierra. By means of the strata on which they lie, these streams are known to have flowed after the end of the Tertiary period. Yet the present rivers have since that time cut great cañons through the lava and into the underlying rock, in some cases at least 2,000 feet deep. Such facts impress us with the immensity of geological times. This important point is discussed more fully in a subsequent part of this work.

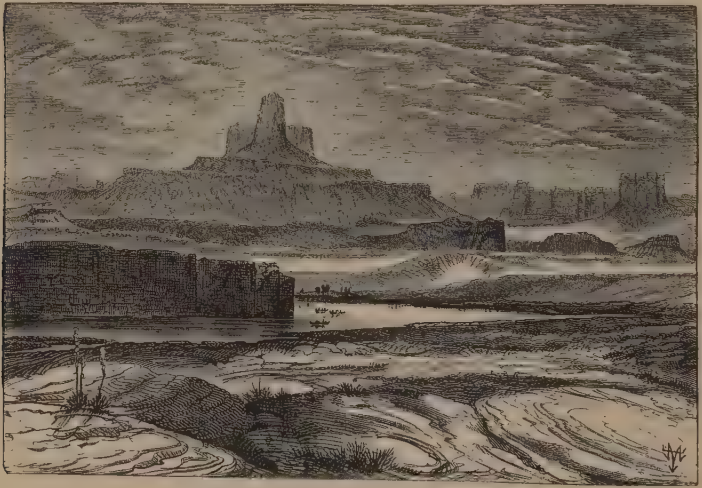

FIG. 9.—Buttes of the Cross (Powell).

But nowhere in this country, or in the world, are the phenomena of cañons exhibited on so grand a scale, and nowhere are they so obviously the result of pure erosion, as in the region of the Grand Plateau of

Utah, Arizona, New Mexico, and Colorado. This plateau is elevated 7,000 to 8,000 feet above the sea, and composed entirely of nearly horizontal strata, comprising nearly the whole geological series from the Tertiary downward. Through this series all the streams have cut their way downward, forming narrow cañons with almost perpendicular walls several thousand feet deep, so that in many parts we have the singular phenomenon of a whole river-system running almost hidden far below the surface of the country, and rendering the country entirely impassable in certain directions (*see* Frontispiece). Nor is the erosion confined to cañons; for the rain-erosion has been so thorough and general that much of the upper portion of the plateau has been wholly carried away, leaving only isolated turrets (*buttes*) or isolated level tables with cliff-like walls (*mesas*) to indicate their original height. All these facts are well shown in Fig. 10. The explanation of these deep and narrow cañons is probably to be found in the predominance of stream-erosion over general disintegration and rain-erosion, which is characteristic of an arid climate (Gilbert).

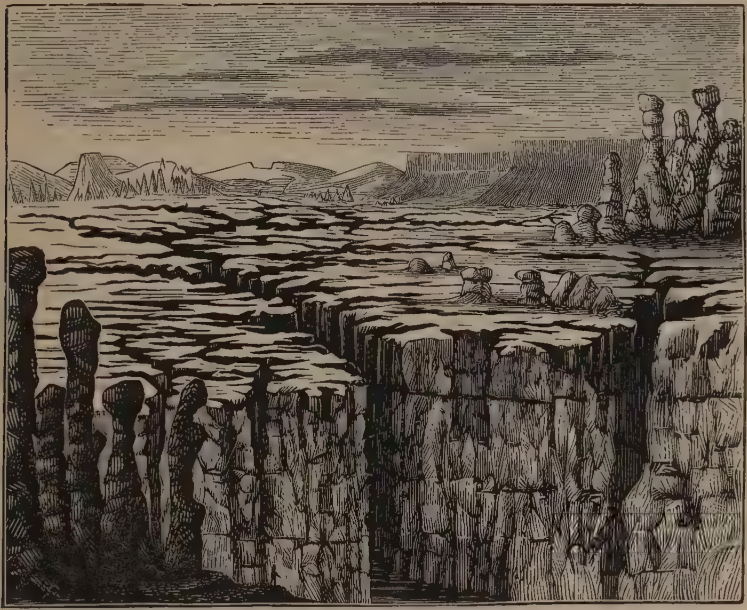

FIG. 10.—Cañon of the Colorado and its Tributaries (from a Drawing by Newberry).

Chief among these cañons is the *Grand Cañon* of the Colorado, 300 miles long and 3,000 to 6,200 feet deep, forming the grandest natural geological section known. Into this the tributaries enter by side-cañons of nearly equal depth, and often of extreme narrowness. Fig. 11 represents the natural proportions of such a cañon.

Time.—These remarkable cañons have evidently been cut wholly by the streams which now occupy them, and which are still continuing the work. The work, probably commenced in the early Tertiary with the emergence of this portion of the continent, became more rapid in the latter portion of the Tertiary with the great elevation of the plateau, and has continued to the present time. Thus, causes now in operation are identified with geological agencies.

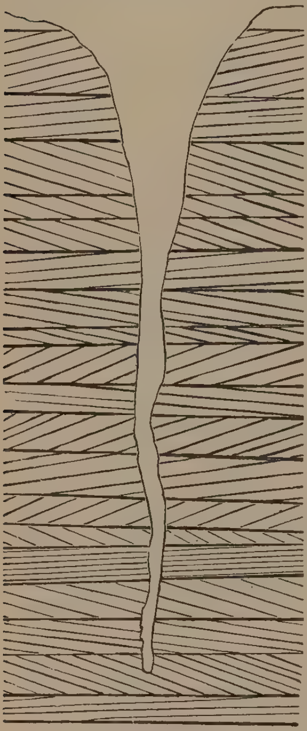

Fig. 11.—Section of the Virgen River (after Gilbert).

In the Appalachian chain gorges and valleys of erosion are abundant, but the evidences of present action are less obvious, and therefore we defer their treatment to Part II, for we are now discussing *agencies still in operation.* Among the more remarkable narrow gorges in this region, we may mention, in passing, the *Tallulah* River gorge, several miles long and nearly 1,000 feet deep, in Rabun County, Georgia, and the gorge of the *French Broad* in North Carolina. The general effects of erosion will be more fully treated under Mountain Sculpture (page 278).

Transportation and Distribution of Sediments.

The specific gravity of most rocks is about 2·5. Immersed in water, they therefore lose nearly half their weight. This fact greatly increases the transporting power of water. The actual transporting power of water is determined partly by experiment and partly by reasoning on the general laws of force. By experiment we determine the transporting power under a given set of circumstances: by general reasoning we determine its law of variation, and apply the data given by experiment to every possible case.

Experiments.—It has been found by experiment that a current, moving at the rate of three inches per second, will take up and carry along *fine clay ;* moving six inches per second, will carry *fine sand ;* eight inches per second, *coarse sand*, the size of linseed ; twelve inches, gravel ; twenty-four inches, pebbles ; three feet, angular stones of the size of a hen's egg.* It will be readily seen from the above that the

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* Page's Geology, p. 28—Rankine.

carrying-power increases much more rapidly than the velocity. For instance, a current of twelve inches per second carries gravel, while a current of three feet per second, only three times greater velocity, carries stones many hundred times as large as grains of gravel. Let us investigate the *law.*

Law of Variation.—If the surface of the obstacle is constant, the force of running water varies as the velocity squared : $f \propto v^2$ (1). This may be easily proved. Suppose we have an obstacle like the pier of a bridge, standing in water running with any given velocity. Now, if from any cause the velocity of the current be *doubled*, since momentum or force is equal to quantity of matter multiplied by velocity ($M = Q \times V$), the force of the current will be *quadrupled*, for there will be double the quantity of water striking the pier in a given time with double the velocity. If the velocity of the current be trebled, there will be three times the quantity of matter striking with three times the velocity, and the force will be increased nine times. If the velocity be quadrupled, the force is increased sixteen times, and so on.

Next, if the velocity of the current remains constant, while the size of the opposing obstacle varies, then evidently the force of the current will vary as the *opposing surface:* if the opposing surface is doubled, the force is doubled; if trebled, the force is trebled, etc. But in similar figures, surfaces vary as the square of the diameter. Therefore, in this case, force varies as diameter squared : $f^1 \propto d^2$ (2). Therefore, when *both* the velocity of the current and the size of the stone or other obstacle *vary*, then the force varies as the square of the velocity of the current multiplied by the square of the diameter of the stone: $F \propto v^2 \times d^2$ (3).

This last equation gives the law of variation of the *moving force.* But the *resistance* to be overcome, or the *weight* of the stone, varies as the cube of the diameters: $W \propto d^3$. We have, therefore, both the law of the moving force and the law of the resistance: $\left\{ \begin{array}{l} F \propto v^2 \times d^2. \\ W \propto d^3. \end{array} \right.$

Now the case we wish to consider is that in which *the current is just able to move the stone*, or when $F \propto W$. In this case $d^3 \propto v^2 \times d^2$, or $d \propto v^2$. Substituting, in the third equation, for d its value, $F \propto v^2 \times v^4 = v^6$. We place these equations together, so that they may be better understood:

When surface = constant . . .	$f \propto v^2$ (1)
When velocity = constant . . .	$f^1 \propto d^2$ (2)
When both vary	$F \propto v^2 \times d^2$ (3)
But	$W \propto d^3$ (4)
And when $W \propto F$, then	$d^3 \propto v^2 \times d^2$
Dividing by d^2	$d \propto v^2$
Substituting in 3	$F \propto v^2 \times v^4$
Or	$F \propto v^6$

That is, *the transporting power of a current or the weight of the largest fragment it can carry, varies as the sixth power of the velocity.* This seems so extraordinary a result that, before accepting it, we will try to make it still clearer by an example.

Let *a* (Fig. 12) represent a cubic inch of stone, which a current of a certain velocity will just move. Now, the proposition is that, if the velocity of the current be doubled, it will move the stone *b*, sixty-four times as large. That it would do so is evident from the fact that the opposing surface of *b* is sixteen times as great as that of *a*, and the moving force would be increased sixteen times from this cause. But the velocity being double, as we have already seen, the force against every square inch of *b* will now be four times that previously against *a*, and, therefore, the whole force from these two causes would be 16 × 4 = 64 times as great. But the weight is also sixty-four times as great; therefore, the current would be just able to move it. We may accept it, therefore, as a law, that the transporting power varies as the sixth power of the velocity. If the velocity, therefore, be increased ten times, the transporting power is increased 1,000,000 times.

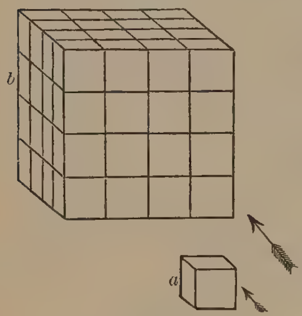

FIG. 12.

We have seen that a current running three feet per second, or about two miles per hour, will move fragments of stone of the size of a hen's egg, or about three ounces' weight. It follows from the above law that a current of ten miles an hour will carry fragments of one and a half ton, and a torrent of twenty miles an hour will carry fragments of 100 tons' weight. We can thus easily understand the destructive effects of mountain-torrents when swollen by floods.

The *transporting* power of water must not be confounded with its *erosive* power. The resistance to be overcome in the one case is *weight*, in the other *cohesion ;* the latter varies as the *square*, the former as the *sixth power* of the velocity. In many cases of removal of slightly cohering material the resistance is a mixture of these two resistances, and the power of removing material will vary at some rate between v^2 and v^6.

There are certain corollaries which follow from the above law:

A. If a current bearing sediment have its velocity checked by any cause, even in a slight degree, a comparatively large portion of the sediment is immediately deposited. But if, on the other hand, the velocity of a current be increased by any cause, in never so small a degree, it will again take up and carry on materials which it had deposited; in other words, it will erode its bed and banks; and these effects are surprisingly large on account of the great change in erosive and transporting power, with even slight changes of velocity.

B. Water, whether still or running, has a wonderful power of *sorting* materials. If heterogeneous material, such as ordinary earth, consisting of grains of all sizes, from pebbles to the finest clay, be thrown into *still water*, the coarse material sinks first to the bottom, and then the next finer, and the next, and so on, until the finest clay, falling last, covers the whole. In *running water* the same sorting takes place even more perfectly, only the different kinds of materials are not dropped upon one another, but successively farther and farther down the stream in the order of their fineness. This property we call the *sorting power of water*. Advantage is often taken of this property in the arts to separate materials of different sizes or specific gravities. By this means grains of gold are separated from the gravel with which it is mingled, and emery or other powders are separated into various degrees of fineness.

We will now apply the foregoing simple principles in the explanation of all the phenomena of currents.

1.—*Relation of Current-Velocity to Erosion and Sedimentation.*

The force of a current is consumed in two ways, viz., by *transportation* and *erosion*. If the current is full-loaded, its whole force is consumed in transportation and none is left over for erosion. Such a river will neither erode nor deposit. If under-loaded, the river will erode; if overloaded, it will deposit. Thus a current of pure water will erode but little, because it carries no graving-tools. If we add sand and gravel, the erosion will increase to a maximum, beyond which it again decreases, because more and more force is consumed in carrying, and less and less is left over for erosion; until finally, in the full-loaded stream, erosion ceases and sedimentation begins. Thus the Platte and Colorado Rivers have about the same slope and velocity; but while the Colorado is deepening its channel, the Platte, on the whole, remains about the same level, sometimes cutting, sometimes depositing. The Colorado is under-loaded, the Platte full-loaded. Again: the Feather River, during floods, is overloaded, and builds up by deposit. During low water it scours out what was previously deposited, even though its velocity is much less.

2.—*Rivers as Indicators of Crust-Movements.*

The level at which a river neither cuts nor deposits is called its base-level. Every river is seeking this level. If above it, it seeks it by cutting; if below it, it seeks it by building up by sedimentation. Rivers thus become delicate indicators of up or down movements of land-surfaces. Suppose a continent to rise gradually and then remain steady; all the rivers would immediately increase their velocity and begin to cut. Now, in making the resulting gorge, two processes are going on, viz., a cutting downward by the river, and a widening out by cliff-crumbling and rain-wash. A V-shaped cañon is thus usually formed, whose shape, whether sharp or wide, will depend on the relative rate of these two processes. They would continue, however, to cut deeper and deeper, until they finally reached their base-level.* Then they would cut no deeper, but sweep from side to side, widening their channels. Meanwhile, rain-wash would continue to cut down their divides until the whole is reduced to a gently undulating surface called a "*peneplain*." Thus wide channels and low divides, or rounded and sweeping curves, are very characteristic of *old* topography, while deep and narrow gorges and cañons are a sign of recent elevation, and therefore comparatively *new* topography. Moreover, successive movements are each faithfully recorded. Thus Fig. 13, which is a section across the Grand Cañon of the Colorado, shows the following events: 1. The plateau region was raised and the river cut down 3,000 feet, and reached its base-level. 2. The river sweeping from side to side, and the crumbling of the cliffs, gradually widened the cañon to its width in the upper part, *b b*. 3. Another rise occurred, and the river again cut 3,000 feet more, and made the inner gorge, *a a*. This second rise is so recent that the river has not yet reached its base-level. Thus there is a regular cycle of topography, which may be compared to infancy, youth, maturity, decline, and death.

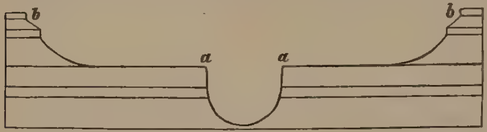

FIG. 13.—Ideal Section across Grand Cañon (after Dutton): *a a*, inner gorge; *b b*, outer cañon walls.

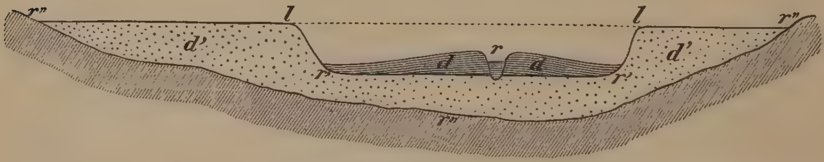

FIG. 14. - Generalized Section across the Mississippi River: r'' r'' r'', old bed; r' r', second bed; r, present bed; d' d', old deposits; d d, present deposits.

On the other hand, suppose a continent, by sinking, carries its river-beds below their base-level: then the decreasing slope will check the velocity of the current, and the rivers will immediately begin to build up again by sedimentation until they again reach their base-level.

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* This, however, would be only a temporary base-level depending on the amount of wash in the upper part of the river. The final base-level is of course the sea-level.

For example, in the Mississippi River the following events are recorded: 1. A higher condition of land, during which it reached its base-level, and formed the broad trough $r'' r'' r''$. 2. A subsidence of land and a building up by sedimentation d' to the level $l\ l$. 3. A partial re-elevation and a cutting down 200 feet, to the level $r' r'$. 4. A resinking and building by alluvial deposit d of about 50 feet. Thus, while on coast-lines, old sea-margins are indicators of crust movements, in the interior of continents river-channels may be used for the same purpose.

3.—*Stratification.*

We have seen that heterogeneous material thrown into still water is completely sorted. This is not stratification, since the various degrees of fineness graduate insensibly into one another. But, if we repeat the experiment, the coarsest material will fall upon the finest of the previous experiment, and then graduate similarly upward. If we examine the deposit thus made, we observe a distinct line of junction between the first and the second deposit. This is *stratification*, or lamination. For every repetition of the experiment a distinct lamina is formed. It is evident, therefore, that to produce stratification two conditions are necessary, namely: 1. An heterogeneous material; and, 2. An intermittently acting cause. Now, these two conditions are always present in Nature where sediments are depositing. Into every body of *still water*, as a lake or sea, rivers bring heterogeneous material torn from the land; but this process is not equable, being increased in the case of small streams by every rain, and in large rivers by the annual floods. Therefore, sedimentary deposits in still water are always stratified.

In *running water* the case is somewhat different. If the stream runs with a velocity at all times the same, then with every repetition of the foregoing experiment the same kind of material falls on the same spot—gravel on gravel, sand on sand, and mud on mud—and there will be no stratification. In running water, therefore, another condition is necessary, namely, a *variable current*. For, when the velocity increases, coarser material will be carried and deposited where finer was previously deposited; when the velocity decreases, finer will be deposited on coarser, and very perfect stratification is the result Now, these three conditions are always present in every natural current. The velocity of every river-current varies not only very greatly in different portions of the year, as in seasons of low water and seasons of flood, but also (from the constant shifting of the subordinate currents of the stream) from day to day, from hour to hour, and even from moment to moment. It follows, therefore, that deposits in running water are also always stratified. Sometimes extreme beauty and distinctness of stratification in the deposits of large rivers are due to the fact that the different branches flood at different seasons, and bring down differently colored sediments.

We may, therefore, announce it as a law, that *all sedimentary deposits are stratified;* and, conversely, that *all stratified masses in which the stratification is the result of sorted material are sedimentary in their origin.* Upon this law is founded almost all geological reasoning.

4.—*Winding Course of Rivers.*

The winding course of rivers is due partly to erosion and partly to sedimentary deposit. It is most conspicuous and most easily studied in rivers which run through extensive alluvial deposit. If the channel of such a river be made perfectly straight by artificial means, very soon some portion of the bank a little softer than the rest will be excavated; this will reflect the current obliquely across to the other side, which will become similarly excavated. Thus the current is reflected from side to side, increasing the excavations. In the mean time, while erosion is progressing on the other side of the curves, because the current is swiftest there, deposit is taking place on the inner side, because there the current is slowest: thus, while the outer curve extends by erosion, the inner curve extends, *pari passu*, by deposit (Fig. 15), and the winding continues to increase, until, under favorable circumstances, contiguous curves on the same side run into each other, as at *a b*, and the curve *c* on the other side is thrown out and silted up. Thus are formed the crescentic lakes or *lagoons* (*l l*) so common in the swamps of great rivers. They are abundant in the swamps of all the Gulf rivers, especially the Mississippi. They are *old beds of the river*, thrown out and silted up in the manner indicated above.

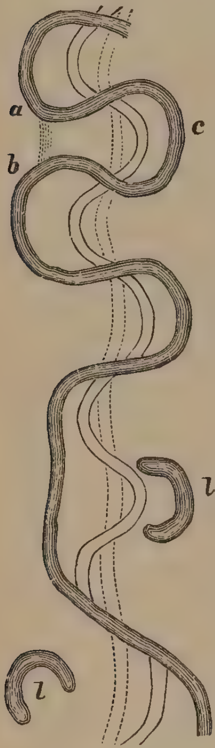

FIG. 15.—Three Successive Stages of a Meandering River.

5.—*Flood-Plain Deposits.*

All great rivers annually flood portions of level land near their mouths, and cover them with sedimentary deposits. The whole area thus flooded is called the *flood-plain*. These flood-plains are very extensive, and the deposits very large, in the case of rivers rising in lofty mountains and flowing in the lower portion of their course through extensive tracts of flat country. In the lofty mountains the current runs with great velocity, and gathers abundant sediment; on reaching the flat country the velocity is checked, the river overflows, and the sediment is deposited. The flood-plain of the Mississippi River is 30,000 square miles. The flood-plain of the Nile is the whole land of Egypt.

The flood-plain of a river may be divided into two parts, viz., the river-swamp and the delta. The river-swamp is that part which was originally land-surface; the delta, that part which has been reclaimed from the sea or lake by the river. We will take up these in succession.

River-Swamp.—We have already seen that, with every recurrence of the rainy season or of the melting of snows, the flooding and the deposition of sediment are repeated. Thus the river-swamp deposit increases in thickness, and the level of the whole flood-plain rises continually. Fig. 16 is an ideal section showing the manner in which the flood-plain is successively built up: *a a a* is the supposed original configuration of the surface, *b b* the successive levels of deposit, *e* the level of the river at low water, and *i i* the level of flood-water.

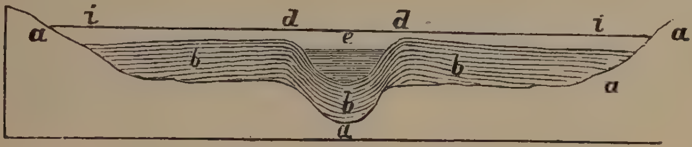

Fig. 16.—Ideal Section of a River subject to Floods.

The extent of such river-swamp deposits is sometimes very great. The river-swamp of the Nile constitutes the whole fertile land of Egypt above the delta. The river-swamp of the Mississippi River, or its flood-plain exclusive of the delta, extends from fifty miles above the mouth of the Ohio to the head of the delta, a distance of about five hundred miles; its average width is over thirty miles, and it includes an area of 16,000 square miles. It is bounded on either side by high bluffs belonging to a previous geological period. The depth of this deposit at the head of the delta is assumed by Lyell to be 264 feet.* But Hilgard has shown that but a small portion of this is alluvium or river deposit of the present epoch.

Natural Levées.—It is seen by the cross-section (Fig. 16) that the level of the river-swamp slopes gently from the river outward, so that the river is bounded on each side by a higher ridge, *d d*. The material of this ridge is coarser than that of the swamp farther back. Such *natural levées* are found along all rivers subject to regular overflows. They are formed as follows: In times of flood the whole flood-plain is covered with water moving slowly seaward. Through the midst of this wide expanse of water runs the rapid current of the river. Now, on either side, just where the rapid current of the river comes in contact with the comparatively still water of the flood-plain, and is checked by it, a line of abundant sediment is determined, which forms the natural levée. Except in very high freshets, these natural ridges are not entirely covered, so that the river in ordinary floods is often divided into three streams, viz., the river proper and the river-swamp water on either side. They can not, however, confine the river within its bank and prevent overflows, since the river-bed is also constantly rising by deposit. Thus the river-bed, the natural levée, and the river-swamp, all rise together, maintaining a certain constant relation to one another.

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* Lyell, Principles of Geology, vol. i, p. 462.

Artificial Levées.—This constant relation is interfered with by the construction of artificial levées. These are constructed for the purpose of confining the river within its banks, and thus reclaiming the fertile lands of the river-swamp. As the bed of the river continues to rise by deposit, the levées must be constantly elevated in proportion; but the river-swamp, being deprived of its share of deposit, does not rise. Thus, under the combined effect of human and river agencies contending for mastery, an ever-increasing embankment is formed, until finally the river runs in an aqueduct elevated far above the surrounding plain. This is very remarkably the case with the river Po, which is said to run in a channel that has been thus elevated above the tops of the houses in the town of Ferrara. Fig. 17 is an ideal cross-section of a river and flood-plain, left at first to the action of natural causes for a time, but afterward interfered with by the construction of artificial levées. The dotted strata show the work of Nature, and the undotted the work of man. It is easy to see that the destructive effects of overflow from accidental crevasses become greater and greater with the elevation. The Po has thus several times broken through its levées and deserted its bed, destroying several villages. The best examples of rivers successfully levéed are those of Italy and Holland. In the case of *Holland* the situation is still worse, for, on account of the sinking of the land, the sea must be diked out as well as the rivers. Here, then, we have a case the extreme opposite of that which we saw in the plateau region (p. 17). In the one case we have a river-system running far *below*, in the other far *above* the general level. In both cases the rivers are seeking their base-levels—in the one case by *cutting*, because the country

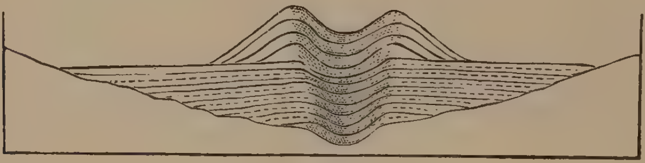

FIG. 17.

is *rising;* in the other by deposit, because the country is sinking. The Mississippi has never been successfully levéed; but, if it should be, it would commence to build up a similar aqueduct, until the whole bed of the river would finally rise above the level of the river-swamp.*

6.—*Deltas.*

Deltas are portions of land situated at the mouths of rivers, and *reclaimed from the sea by their agency.* Over the flat surface of the delta the river runs by inverse ramification, and empties by many mouths. They are usually of irregular triangular form, the apex of the triangle pointing up the stream. The delta of the Nile (Fig. 18) is perhaps the best example of the typical form. As seen in the figure, at the head of the delta the river divides into branches, and communicates with the sea by many mouths. The area of land thus made varies with the size of the river, the proportion of sediment in its waters, and the time it has been making sedimentary accumulations. The delta of the Nile is 100 miles long and 200 miles wide at its base; that of the Ganges and Brahmapootra is 220 miles long and 200 miles wide at its base, comprising an area of 20,000 square miles. The delta of the Mississippi (Fig. 19) is very irregular in form, and is an admirable

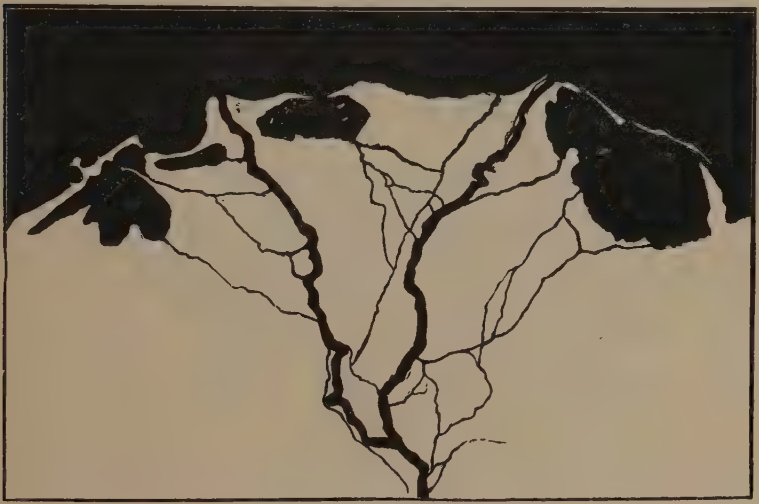

FIG. 18.—Delta of the Nile.

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* It is probable that the effect of levées in raising the river-bed has been greatly exaggerated. Recent observations on the Po seem to show that the elevation is confined to the upper reaches of the flood-plain region, being prevented in the lower course by the increased velocity of the current produced by levées.

illustration of the manner in which each mouth pushes its way into the sea. Its area is estimated at 12,300 square miles. The materials of which deltas are composed are usually the finest sands and clays, all the coarser materials having been deposited higher up the stream.

Deltas are formed only in *lakes* and *tideless* or nearly *tideless seas.* In tidal seas, the sediments brought down by the rivers are swept away and carried to sea by the retreating tide; and instead of the land encroaching upon the domain of the sea by the formation of deltas, the sea encroaches upon the land by the erosive action of the tides, and forms bays or *estuaries.* Thus in tideless seas or lakes the rivers empty by many slender mouths, while in tidal seas they empty by wide bays: thus, for example, all the rivers emptying into the great Canadian lakes, and all the rivers emptying into the Gulf of Mexico, form deltas, while all the rivers emptying into the Atlantic in both North and South America form estuaries. In Europe all the rivers emptying into the Black, the Caspian, the Mediterranean, and the Baltic, form deltas, while those emptying into the Atlantic form estuaries.

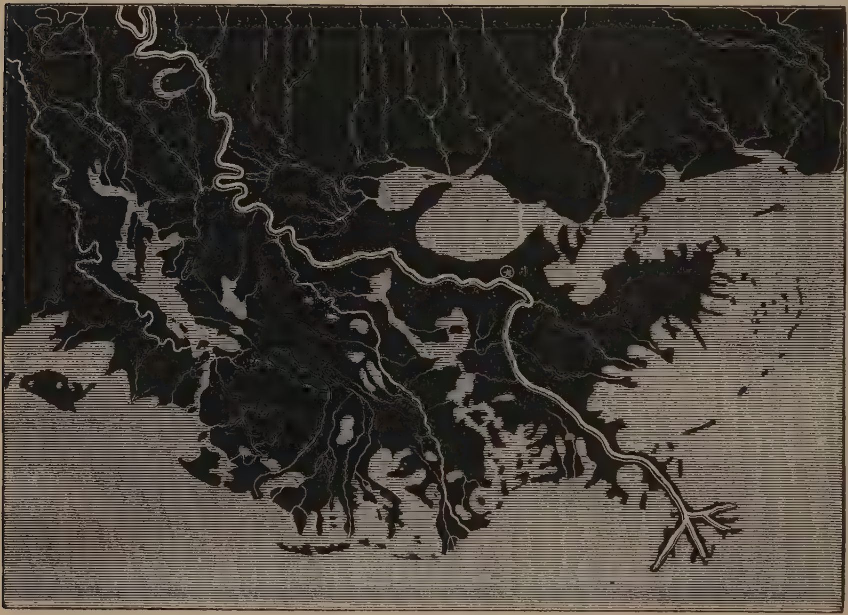

Fig. 19.—Delta of the Mississippi.

Process of Formation.—The process of formation of a delta may be best studied by observing it on a small scale, in the case of streamlets running into ponds. In such cases we observe always a sand or mud flat at the mouth of the streamlet, evidently formed by the sand

and clay brought down by the current. As soon as the current strikes the still water of the pond, its velocity is checked, and its burden of sediment is deposited. Through the sand-flat thus formed the streamlet ramifies, as seen in Fig. 20. The ramification seems to be the result of the choking of the stream by its own deposit, which forces it to seek new channels. The sand-flat is gradually extended farther and farther into the pond by successive deposits, as shown in Fig. 20. Fig. 21 shows the irregular stratified appearance of the deposits as seen on cross-section. In all such cases of streams flowing into ponds or lakes, the stream flows *in* at *a* muddy, but flows *out* at *b* comparatively clear, having deposited much of its sediment in the pond or lake. Evidently if this process continues without interruption, the pond will eventually be filled up, after which, of course, the sediment will be carried farther down the stream. In this manner small mountain-lakes are often entirely filled up. The Rhône flows into Lake Geneva a turbid stream, but flows out beautifully transparent. The whole of its sediment is deposited where it enters the lake, and it has there formed a delta six miles long. We may confidently look forward to the time, though many thousand years distant, when this lake will be entirely filled up. After leaving the lake the Rhône again gathers sediment from tributaries flowing in below the lake, and forms another delta where it empties into the Mediterranean. Many examples of lakelets partially filled, or entirely filled and converted into meadows, are found among the Sierra Mountains. If lakes are drained away or dried away, old deltas are found on the slopes at the level of their old margins. Many such are seen about Great Salt Lake. These might be called fossil deltas.

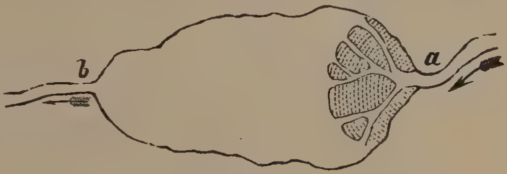

Fig. 20.

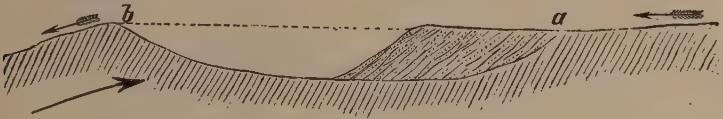

Fig. 21.

In the section view (Fig. 21) we have represented the strata as irregular and highly inclined. This is called *oblique lamination.* This can only occur when a rapid stream, bearing abundant *coarse material,* rushes into still water. But, in the case of large rivers flowing long distances and bearing only the finest sediment, the stratification is much *more regular and nearly horizontal.*

Rate of Growth.—There have been several attempts to estimate the rate of growth of deltas, in order to base thereon an estimate of their age. The delta of the Rhône in Lake Geneva has advanced at least one and a half mile since the occupation of that country by the Romans; for the ancient town Portus Valesiæ (now Port Valais), which stood then on the margin of the lake, is now one and a half mile inland. The delta of the same river at its mouth in the Mediterranean is said to have advanced twenty-six kilometres, or sixteen miles, since 400 B. C., or thirteen miles during the Christian era.* The delta of the Po has advanced twenty miles since the time of Augustus; for the town Adria, a seaport at that time, is now twenty miles inland. But the most elaborate observations have been made on the Mississippi. This river, as seen in Fig. 19, has pushed its way into the Gulf in a most extraordinary manner. According to Thomassy,† and also Humphrey and Abbot, the rate of advance is about one mile in sixteen years. The rate of progress in the deltas mentioned has, however, probably not been uniform. There are special reasons for their more rapid advance at the present time. In the case of the Po, the successful levéeing of this river has transferred to the sea the whole of the sediment which would otherwise have been spread over the flood-plain. In the case of the Mississippi, for many centuries the principal portion of the deposit has been confined to a narrow strip but a few miles wide, and the advance has been proportionately rapid. For this reason the river has run out to sea for more than fifty miles, confined only by narrow strips of land, *the continuation of the natural levées*. These marginal ridges are continued as submarine banks even much beyond the present mouths of the river. The rate of advance of the Nile delta seems to be much slower.

Age of River-Deposits.—The age of *river-swamp* deposits may be estimated by determining their absolute thickness and their rate of increase. The river Nile is peculiarly adapted for estimates of this kind, because we have on its alluvial deposits the seat of the oldest civilization and the oldest known monuments of human art. These monuments, the ages of which are approximately known, are many of them more or less buried in the river-deposit. At Memphis, the foundation of the colossal statue of Rameses II, over 3,000 years old, was found in 1854, buried about nine feet in river-deposit.‡ This makes the rate of increase of the deposit three and a half inches per century. Experiments at Heliopolis bring out nearly the same result. The whole depth of the alluvial deposit at Memphis was found to be about forty feet, which, at the above rate, would make the age of the deposit at this point about 13,500 years. But this all belongs to the human epoch, for bricks have been found beneath the lowest part. The alluvial deposit of the Nile is much thicker at some points than forty feet; but, on the other hand, the rate of increase for different places is probably variable.

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* Archives des Sciences, vol. li, p. 157.

† Géologie pratique de la Louisiane.

‡ Philosophical Magazine, vol. xvi, p. 225.

The age of a *delta* is usually estimated by dividing the cubic contents of the delta by the annual mud-discharge. The cubic contents of the delta are estimated by multiplying the superficial area by the mean depth. The mean depth of the Mississippi delta, as determined by borings, is taken by Mr. Lyell as 528 feet, the superficial area at 13,600 square miles, and the annual mud-discharge at 7,400,000,000 cubic feet. Upon these data he makes the probable age of the delta 33,500 years. To this he adds half as much for the age of the river-swamp, making in all 50,000 years.

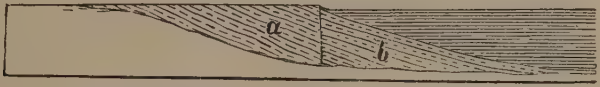

Fig. 22.—Ideal Section of Delta and Submarine Bank.

It is evident, however, that this estimate can not be relied on as even approximately accurate. For there is no reason why the time of river-swamp deposit should be added to that of the delta, for they were both probably formed at the *same time*—one by deposits higher up the river, the other by deposits at the mouth. Again, on the other hand, the estimate takes no account of the *submarine extension of the delta*, in area certainly, and in cubic contents probably, much greater than the subaërial delta. Figs. 22 and 23 are an ideal section and a map of a delta in which *a* is the aërial and *b* the submarine portion. This would greatly increase the time.

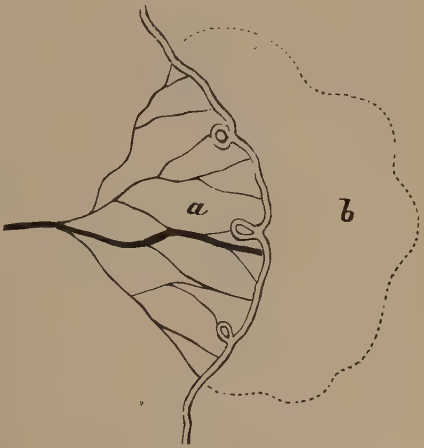

Fig. 23.—Delta and Submarine Bank.

It is evident, therefore, that although the problem is one of great interest, we are not yet in possession of data to make a reliable estimate. Every estimate, however, indicates a very great lapse of time.

But it must not be imagined, as all estimaters seem to do, that this time, be it greater or less than Mr. Lyell's estimate, belongs all to the present geological epoch. Prof. Hilgard has shown that the true alluvial deposit of the Mississippi is only *fifty to one hundred feet thick.* Beneath this the deposit belongs to the Quaternary or preceding geological epoch.

7.—*Estuaries.*

We have already seen that rivers which empty into tideless seas communicate with the sea by numerous branches traversing an alluvial flat, formed by the deposits of the river; while rivers emptying into tidal seas communicate by wide mouths or bays, formed by the erosive action of the flowing and ebbing tide. Such bays are called *estuaries.* We have fine examples of estuaries in the Amazon and La Plata Rivers, in the Delaware and Chesapeake Bays, in the friths of Scotland and the fiords of Norway; in fact, at the mouths of all the rivers emptying into the Atlantic on our own coast as well as on the European coast. The mouth of the Columbia River is a good example on the Pacific coast. The phenomena of a delta and an estuary are sometimes combined in the same river. This is the case to some extent in the Ganges.

Mode of Formation.—Estuaries are evidently formed by the erosive action of the inflowing and outflowing tide. Their shape, narrow above and widening toward the sea, gives great force to the tidal current, which, entering below and concentrated in the ever-narrowing channel, rushes along with prodigious velocity and rises to an immense height. In the Bay of Fundy the tide rises seventy feet, and at Bristol, England, it rises forty feet, in Puget Sound twenty-five feet. Sometimes, from obstructions at the mouth of the river, the tide enters as one or more immense waves, rushing along like an advancing cataract. This is called an *eagre* or *bore.* The finest examples are perhaps in the Amazon and Tsien-tang Rivers. In the eagre of the Amazon "the tide passes up in the form of three great waves, thirteen to twenty-three feet high." * In the Tsien-tang, a single wave plunges along at the rate of twenty-five miles an hour,† with perpendicular front, like an advancing cataract, four or five miles wide and thirty feet high. In the river Severn also we have a remarkable example of an eagre. According to the laws already developed (pp. 19 and 20), the erosive and transporting power of such currents must be immense.‡

Deposits in Estuaries.—The larger portion of the materials thus eroded is carried out to sea by the retreating tide, and will be again spoken of under "Sea-deposits." A portion of these materials, however, is always deposited in the estuary in sheltered coves and bays (Fig. 24, *a* and *b*), and often, when the outflowing tide is obstructed by sand-spits and islands at the mouth, over every portion of the estuary. In addition to this, especially in rivers subject to great freshets, there are deposits of silt from the river. Thus many estuaries are occupied alternately, during the wet and dry seasons, by fresh and brackish or salt water, and the deposits in them are therefore alternately fresh-water and salt-water deposits, containing fresh-water and salt or brackish water shells. These alternations are highly characteristic of estuary-deposits in all geological periods; in fact, of all deposits at the mouths of rivers where river and ocean agencies meet.

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* Branner, Science, 1884, vol. iv, p. 488.

† American Journal of Science and Arts, 1855, vol. xx, p. 305.

‡ In many cases estuaries may be the result of subsidence of the land and invasion of the lower courses of the rivers by the sea.

8.—*Bars.*

Bars are invariably formed in accordance with the law already enunciated as that controlling all current-deposits, viz., if the velocity of a current-bearing sediment be checked, the sediment is deposited.

There are two positions in which bars are formed: 1. At the mouths of rivers; and, 2. At the head of the estuaries. In the first position (Fig. 24, *d d*) the bar is formed by the contact of the river-current with the still water of the ocean. It is most marked in the case of estuaries. The outflowing tide scours out the estuary, carrying with it sediment partly brought down by the river, and partly the *débris* of land eroded by the inflowing tide. The larger portion of this is dropped as soon as the tidal current comes in contact with the open sea and is checked by it. They are usually irregularly crescentic in form. Such are the bars at the mouths of all harbors. In the second position they are found just where the upward current of the inflowing tide meets the downward current of the river, and makes *still water*. At this point we have not only a bar, but usually also an extensive marsh caused by the daily overflow of the river. Through this marsh the river winds in a very devious course, as if common in all rivers whose banks are alluvial.

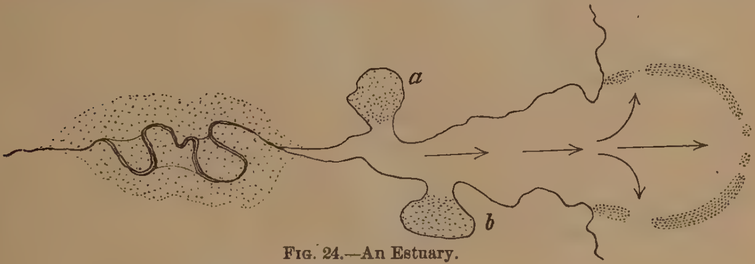

Fig. 24.—An Estuary.

Thus, then, in rivers like the Mississippi, emptying into tideless seas and forming deltas, there is but one bar, viz., that at the mouth; while in rivers forming estuaries there are two bars, an *outer* and an *inner*. This inner bar may be many miles up the river. In the Hudson River the inner bar is a hundred and forty miles up the river, and only a few miles below Albany. This is really the head of tide-water in this river.*

Bars, being produced by natural and constantly-acting causes, *can not usually be permanently removed*, though they may be sometimes greatly improved. If they are scraped away by dredging-machines, they are speedily reformed on the same spot. If we cause the river itself to remove them, as has sometimes been done by narrowing the channel and thus increasing the erosive power, we indeed remove the bar, but it is reformed farther down-stream at a new point of equilibrium. In some cases, however, bars have been *permanently* removed. This has been done for the Danube, and recently by Capt. Eads for the Mississippi, by the construction of jetties running out to deep water. These confine the current, increase its velocity, and cause the river to scour away its bar, and thenceforth to deposit its sediment in water so deep that it will require centuries to build up again from the bottom, and re-form the bar.

We have thus traced river agencies from their source to the sea. This brings us naturally to ocean agencies.

SECTION 2.—OCEAN.

Waves and Tides.

Waves.—Waves produce no current, and therefore no geological effect in deep water. The erosive effect of this agent is almost entirely confined to the coast-line, but at this point is incessant and powerful. The average force of waves on the west coast of Scotland for the summer months is estimated by Stevenson at 611 pounds per square foot, and for the winter months at 2,086 pounds per square foot.† In violent storms the force is estimated at 6,000 pounds per square foot,‡ and fragments of rock of many hundred tons' weight are often hurled to a considerable

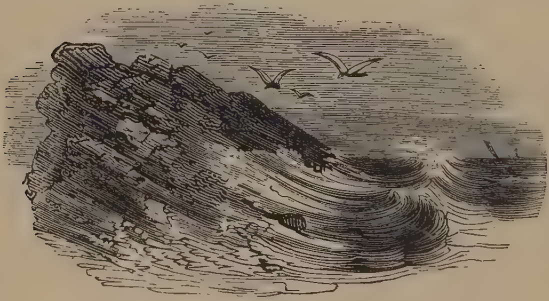

FIG. 25.

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* There is another important principle affecting the formation of bars in rivers emptying into seas, viz., the flocculation and consequent precipitation of clay sediments, by salt-water (Hilgard).

† Dana's Manual, p. 654.

‡ Herschel's Physical Geography, p. 75.

distance on the land. These fragments hurled against the shore are the principal agent of wave-erosion. The rapidity of the erosion of a coast-line by the action of waves is determined partly by the softness and partly by the inclination of the strata. If the strata turn their faces to the waves, particularly if inclined at a small angle, the effect of the waves is comparatively slight (Fig. 25); but, if the edges of the strata are exposed to the waves, the erosion is much greater. For instance, if the strata be horizontal, as in Fig. 26, then the strata are undermined and form overhanging table-rocks, which from time to time fall into the sea; if the strata are vertical or highly inclined and their edges turned to the sea, then an exceedingly irregular coast-line is formed and the erosion is very rapid, as the force of the waves is concentrated upon the re-entering angles. Fig. 27 is a map view of a coast, in which from *a* to *b* the waves strike the edges, while from *a* to *c* they strike the faces of the same rocky strata. The arrow shows the direction of the dip of the strata. The difference in the form of the coast-line is seen at a glance.

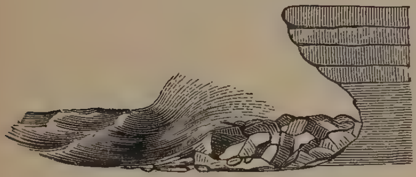
FIG. 26.—Section of an Exposed Cliff.

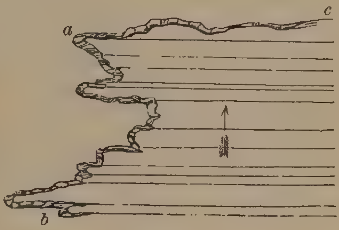

FIG. 27.

Waves, cutting ever at the shore-line only, act like an *horizontal saw.* The receding shore-cliff, therefore, leaves behind it an ever-increasing subaqueous platform which marks the amount of recession. This is shown in the section (Fig. 28), in which *s* is the present shore-line, *l* the water-level, *a b* the platform, *s'* the original shore-line, and *s' b c* the original slope of bottom. The recession of the shore-line and the formation of the shore platform have been accurately observed in Lake Michigan (Andrews). Level platforms terminated by cliffs, therefore, when found inland, sometimes indicate the position of old shore-lines. If the land should be subsequently elevated, these remain and mark the former margins of the sea.

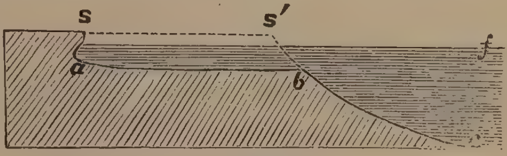

FIG. 28.

Tides.—The tide is a wave of immense base, and three or four feet in height in the open ocean, produced by the attractive force of the moon and sun on the waters of the ocean. The velocity of this wave is very great, since, if unobstructed, it would travel around the earth in twenty-four hours. In the open ocean it produces very little current, only a slow transfer of the water back and forth, too slow to produce any geological effect;[*] but in shallow water, where the progress of the wave is impeded, it piles up in some cases forty to fifty feet in height, and gives rise to currents of great velocity and immense erosive power. By this means bays and harbors are formed, and straits and channels are scoured out and deepened. Tides also act an important part in assisting the action of waves upon the whole coast-line. The action of waves on exposed cliffs quickly forms accumulations of *débris* at their base, composed of sand, mud, shingle, or rocky fragments (Fig. 26), which receive first and greatly diminish the shock of the waves upon the cliff. The incessant beating of the waves upon this *débris* reduces it to a finer and finer condition, and the retreating waves bear much of it seaward; so that, even without the assistance of any other agent, the protection is incomplete, and the erosion therefore progresses. But if strong tidal currents run along the coast, these effectually remove such *débris* and leave the cliff exposed to the direct action of the waves.

Examples of the Action of Waves and Tides.—The coasts of the United States show many examples of the erosive action of waves and tides. The form of the whole New England coast is largely determined by this cause. The softer parts are worn away into harbors by the waves and scoured out by the tides, while the harder parts reach out like rocky arms far into the sea. Sometimes only small rocky islands, stripped of every vestige of earth, mark the position of the former coast-line. Boston Harbor and the rocky points and islands in its vicinity are good examples. The process is still going on, and its progress may be marked from year to year.

On the Southern coast examples of a similar process are not wanting. At Cape May, for instance, the coast is wearing away at a rate of about nine feet per annum. The more exposed portions about Charleston Harbor, such as Sullivan's Island, are said to be wearing away even more rapidly. As a general fact, however, the low, sandy, or muddy shores of the Southern coasts are receiving accessions more rapidly than they are wearing; while, on the contrary, the New England coast, as proved by its rocky character, is losing much more than it gains. The shores of Lake Superior (Fig. 29) furnish many beautiful examples of the action of waves—in this case, of course, unassisted by tides. The general form of the lake along its south shore is determined by the varying hardness of the rock; the two projecting promontories La Pointe (*a*) and Keweenaw Point (*c*) being composed of hard, igneous rocks, while the intervening bays *b* and *d* are softer sandstone. On the south shore, about *e*, between La Pointe and Fond du Lac (*f*), the conditions of rapid erosion are beautifully seen. The shores are sandstone cliffs, with nearly horizontal strata. These have been eroded beneath by the waves, in some places for hundreds of feet, forming immense overhanging table-rocks, supported by huge sandstone pillars of every conceivable shape. Among these huge pillars, and along these low arches and gloomy corridors, the waves dash with a sound like thunder. From time to time these overhanging table-rocks, with their load of earth and primeval forests, fall into the lake.

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[*] Herschel's Physical Geography, p. 64.

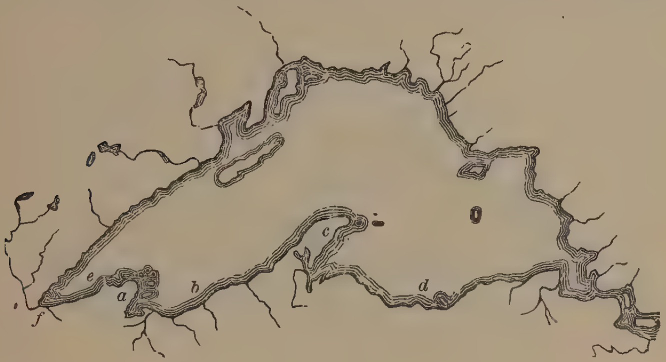

FIG. 29.—Lake Superior.

The coasts of Europe furnish examples on a more magnificent scale, and have been more carefully studied. The cliffs of Norfolk are carried away at a rate of three feet, and those of Yorkshire six feet, annually. The church of the Reculvers, on the coast of Kent, near the mouth of the Thames, stood, in the time of Henry VIII, one mile inland. Since that time the sea has steadily advanced until, in 1804, a portion of the churchyard fell in, and the church was abandoned as a place of worship. The church itself, ere this, would have been undermined and fallen in, had it not been protected by artificial means. There are many instances in the German Ocean of islands which have been entirely washed away during the historic period.

The tidal currents through the British and Irish Channels, along the western coasts of Ireland and Scotland, among the Orkneys and Hebrides, and especially along the coast of Norway, are very powerful. Along this latter coast it forms the celebrated Maelstrom. The erosive effects of the sea are, therefore, very conspicuous. On the south and east coast of England the erosion is now progressing rapidly. On the west coast of Ireland and Scotland the waste is not now so great, because the softer material is all removed, but the configuration of the coast shows the waste which it has suffered. A glance at a good map of Ireland shows a deeply-indented western coast, composed entirely of alternating rocky promontories and deep bays. On the western coast of Scotland, and especially on the Orkney, Shetland, and Hebrides islands, the wasting effect of the sea has been still greater. Not only have we here the same character of coast as already described (as seen in the friths of Scotland), but many small islands have been eroded, until only a nucleus of the hardest rock is left; and even these have been worn until they seem but the ghastly skeletons of once fertile islands. Figs. 30 and 31 will give some idea of the appearance of these spectral islands.

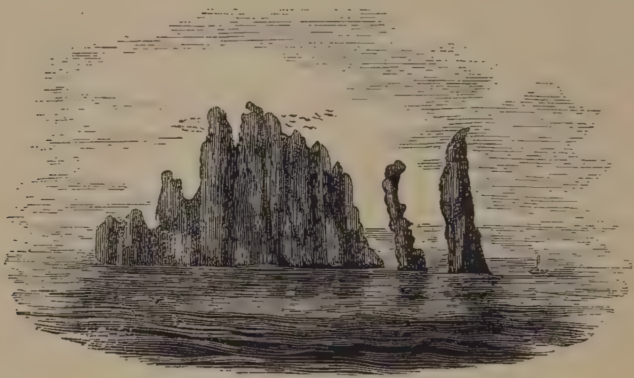

Fig. 30.

The coast of Norway consists entirely of deep fiords alternating with jutting headlands of hardest rock several thousand feet high. Along this intricately-dissected coast there runs a chain of high, rocky islands, which in an accurate map is scarcely distinguishable from the coast itself, being separated only by narrow, deep fiords. Toward the

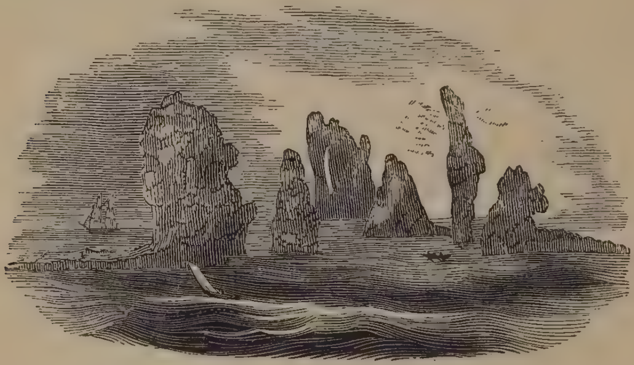

Fig. 31.

northern part of the coast the crest of the Scandinavian chain seems to run directly along the jutting promontories of the coast-line, for these headlands are the most elevated part of the country; in fact, in some parts it would seem that the original crest was at one time still farther west, along the line of coast-islands. If so, then the sea has not only carried away the whole western slope, but has broken through the main axis, leaving only these isolated rocky islands as monuments of its former position, and is even now carrying its ravages far inland on the eastern slope. In the case of Norway, however, and probably in case of nearly all bold, rocky coasts, the intricacy of the coast-line is not due wholly or even principally to the action of waves and tides, but also to other causes, mainly subsidence, to which we shall refer hereafter.

Transporting Power.—The transporting power of waves is immensely great, often taking up and hurling on shore masses of rock hundreds of tons in weight; but, being entirely confined to the coast-line, the *distance* to which they carry is necessarily very limited. There are some instances, however, of materials carried to great distances by the incessant action of waves. Thus, according to Prof. Bache, coast-sand is carried slowly farther and farther south by the action of waves, and siliceous sand is found at Cape Sable on the extreme southern point of Florida, although the whole Florida coast as far as St. Augustine is composed of coral limestone alone. He accounts for this by supposing that the trend of the United States coast is such that waves coming from the east strike the coast obliquely and fall off toward the south, carrying each time a little sand with them. A similar phenomenon has been observed on Lake Michigan; the sands are carried steadily toward the south end, where they accumulate.

Deposits.—The invariable effect of waves, chafing back and forth upon coast *débris*, is to wear off their angles and thus to form rounded fragments and granules. Thus, pebbles, shingle, and round-grained sand, though produced by all currents, are especially characteristic of wave-action. *Ripple-marks* are also characteristic of current-action in shallow water. They are, therefore, always formed on shore by the action of waves and tides. By means of these characteristics of shore deposit, many coast-lines of previous geological epochs have been determined.

We have seen that waves usually *destroy* land. In many cases, however, they also *make* land. This is the case whenever other agencies, such as river or tidal currents, drop sediment in shallow water, and therefore within reach of wave-action. We shall again speak of these under the head of Land formed by Ocean Agencies.

Oceanic Currents.

The ocean, like the atmosphere, is in constant motion, not only on its surface, but throughout its whole mass. The general direction of the currents in the two cases is also similar, but there are disturbing and complicating causes peculiar to each, which interfere with the regularity and simplicity of the phenomena. If the currents of the atmosphere are more variable on account of the greater levity of the fluid, oceanic currents have also their peculiar disturbing causes in the existence of impassable barriers in the form of continents. In both atmosphere and sea, currents may also be deflected by *submarine banks*, for mountain-chains are the banks of the aërial ocean.

Theory of Oceanic Currents.—By some distinguished physicists, oceanic currents have been attributed entirely to the action of the *trade-winds.** There can be no doubt that this is a *real cause ;* yet it seems probable, nay, almost certain, that the great and controlling cause of currents of the ocean, as of the air, is difference of temperature between the equatorial and polar regions.

General Course of Oceanic Circulation.—We leave it for physicists to determine the true theory of oceanic currents. Suffice it to say that on either theory the general course of circulation would be much the same. An equatorial current stretches across both the great oceans from east to west, impinges against the continent, turns northward and southward to about 45° or 50° latitude, then eastward, then southward and northward to form again the equatorial current (Fig. 32). The details of their courses may be made more complex by the configuration of continental margin and of sea-bottom. We take as example the

Gulf Stream.—Currents coming from the north and south on the African coast (*b b′*, Fig. 32) unite to form an equatorial current, *c c′*, which stretches across the Atlantic until, striking against the coast of South America, it turns north and south, *a a′*. The southern branch turns gradually eastward, *d′*, and forming a grand circle in the southern Atlantic joins again the South African current *b′*. The northern branch, *a*, runs along the coast of South America, through the Caribbean Sea and into the Gulf of Mexico, from which emerging it runs with great velocity through the narrow straits of Florida and thence under the name of the Gulf Stream along the coast of North America, turning more and more eastward in obedience to the law already mentioned, until it becomes an eastward current, *d*, about 50° latitude; and then stretches across to the coast of Europe, and turns again southward to join the equatorial current. A portion of it, however, in its eastward course turns northward, *e*, and returns as a cold polar current, *e″*, hugging the shore of North America as a *cold wall* to the Gulf Stream, and thus passes south.

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* Herschel, Physical Geography, p. 13; and Croll, Climate and Time.

Geological Agency of Oceanic Currents.—The velocity of oceanic currents is generally small, although, in the case of the Gulf Stream, at the Florida Straits, it reaches almost the velocity of a torrent, viz., three and a half to five miles per hour. The volume of water carried by them is almost inconceivably great; it is estimated that the Gulf Stream alone carries many times more water than all the rivers of the globe. According to Croll, it is equal to a current fifty miles wide and one thousand feet deep, running at a rate of four miles per hour. The geological agency of these powerful currents in modifying the bottom of the sea by erosion *may* be, and by sedimentary deposit *must* be, very important, though as yet comparatively little known.

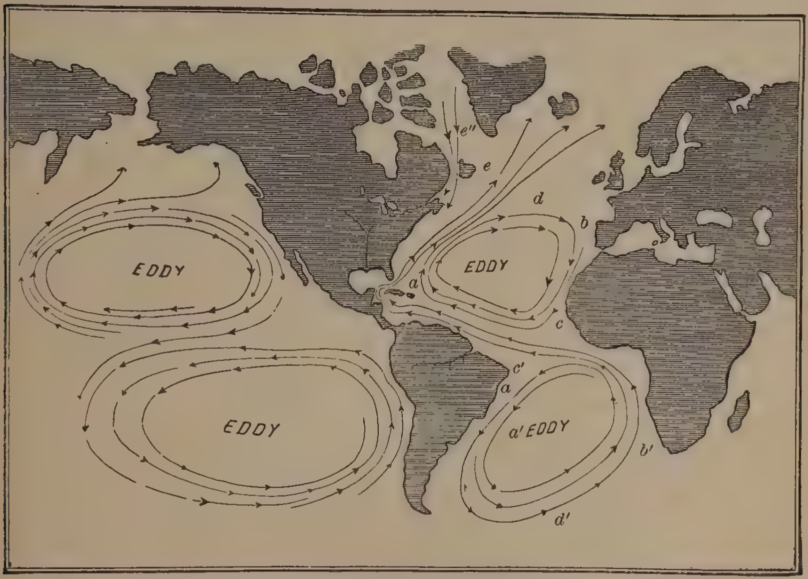

Fig. 32.—General Course of Oceanic Currents.

One of the chief functions of oceanic currents is the transportation and distribution over the open-sea bottom of sediments brought down by the rivers. By far the larger part of the *débris* of the land is certainly dropped near the shore, and marginal sea-bottoms are everywhere the great theatres of sedimentation; but, without the agency of marine currents, none would reach open sea; *all* would be dropped near shore.* By the agency of these, however, the *finer* portions are carried and widely distributed over certain portions of deep-sea bottoms. We have undoubted evidence of this in some cases. Thus the sediments brought down by the Amazon are swept seaward by a strong tide, and then taken by the oceanic current which sweeps along that coast, and carried 300 miles and deposited much of it on the coast of Guiana. According to Humboldt, the same stream carries sediment from the Caribbean into the Gulf of Mexico.* There is little doubt, too, that much of the sediments brought into the Gulf of Mexico by the Gulf rivers is swept along by the Gulf Stream, and a part of it deposited on Florida Point and the Bahama Banks. The surface transparency of the Gulf Stream is no objection to this view, as a little reflection will show. Ocean-currents differ from rivers, in the fact that the former run in perfectly smooth *beds of still water*. There are, therefore, no subordinate currents from side to side, or up and down, whereby in river-currents the water is thoroughly mixed up, and the finer sediments prevented from settling. In ocean-currents the conditions are as favorable for subsidence as in still water. It is evident, therefore, that sediments carried by ocean-currents must in a little time sink out of sight, although from the great depth of these currents they may still be carried to considerable distances. Deep-sea deposits have until recently received little attention, although they are acknowledged to be of the greatest geological importance.

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* Undoubtedly a large portion of the deep-sea bottom is never reached by mechanical sediments. This is strikingly shown by the fact that one haul of the dredge of the

Some Effects of the Co-operation of the Preceding Agencies—Submarine Banks.—These are usually accumulations of material dropped by currents. They are formed under conditions similar to those which determine the formation of bars; i. e., either by the meeting of opposing sediment-laden currents or else by such a current coming in contact with still water. In fact, the outer bar is a true submarine bank. The currents may be either tidal or oceanic or river. Admirable examples of both those modes of formation are found in the German Ocean. The tidal wave from the Atlantic strikes the British Isles, passes round in both directions, and enters this ocean from the north around the north point of Scotland, and from the south through the British Channel and Straits of Dover (Fig. 33). These two currents coming from opposite directions meet and make still water, and therefore deposit their sediment and form banks. Again, the tidal current is concentrated in the British Channel, and runs with great velocity, scouring out this channel, and in addition gathering abundant sediment from the rivers emptying into the channel. Thus loaded with sediment it rushes through the narrow Straits of Dover, and, coming in

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Challenger brought up 600 fossil shark's teeth and 100 ear-bones of whales. These fossils were probably Eocene. If so, their age is almost inconceivable. And yet they lay still uncovered on the sea-bed.—Bull. Geol. Soc. Am., vol. ii, p. 13, 1891.

* Lyell's Principles of Geology.

contact with the still water of the German Sea, forms eddies on either side, and deposits its sediments. Besides the banks thus formed, there are, of course, bars formed at the mouths of the rivers emptying into this shallow sea. By a combination of all these causes, we explain the numerous banks which render the navigation of this sea so dangerous.

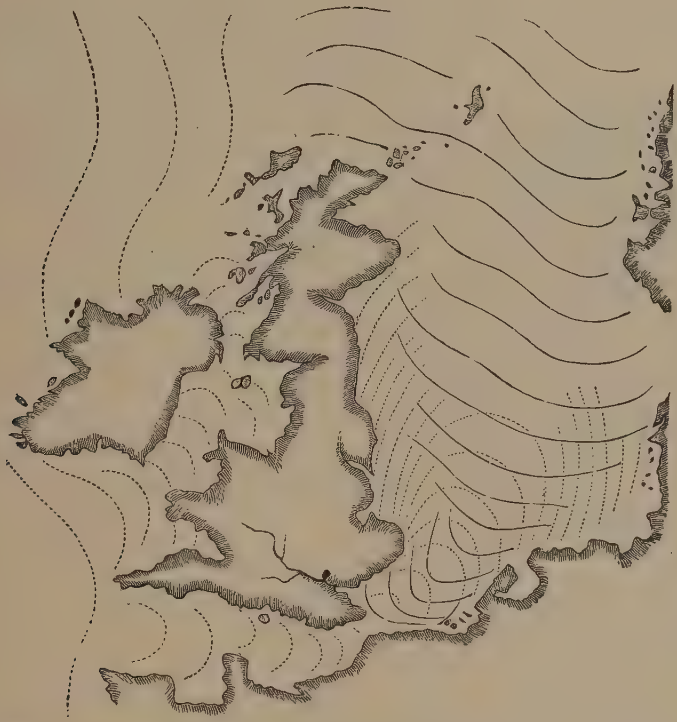

FIG. 33.—Tides of the German Ocean. The curved lines represent successive positions of the advancing tide.

But great banks far away from shore are usually formed by oceanic currents. Thus the Banks of Newfoundland are evidently formed, partly at least, by the meeting of the polar current (e'', Fig. 32), bearing icebergs loaded with earth, and the warm current of the Gulf Stream, perhaps also bearing its share of fine sediment. Again, the Gulf Stream, rushing at high velocity (four miles per hour) through the narrow Straits of Florida, coming in contact with the still water of the Atlantic beyond and forming eddies on each side, and depositing sediment, has certainly contributed to form, if it has not wholly formed, the Bahama Banks on one side, and the bank on which the Florida reefs are built on the other. It is probable that many other peculiarities of the Atlantic bottom in the course of the Gulf Stream may be similarly accounted for.*

Land formed by Ocean Agencies.—Upon submarine banks, however these may be produced, are gradually formed islands. These islands are always formed by the immediate agency of waves. As soon as the submarine bank rises so near the surface that the waves touch bottom, and form breakers, these commence to throw up the sand or mud until an island is formed, which continues to grow by the same agency, until it becomes inhabited by plants and animals, and finally by man. The height of such islands above the sea will depend upon the height of the tides and the force of the waves. They are seldom more than fifteen feet above high water. Thus we find that extensive banks are always dotted over with islands. In this manner are formed the low islands so common about the mouths of harbors and estuaries, also the narrow *sand-spits* all along our Southern coast, separating the harbors and sounds from the ocean. Fig. 34, which is a map of the North Carolina coast, will give a good idea of these sand-spits. In the course of time such sounds, being protected in some measure by the sand-spits from the scouring action of the tides, are gradually filled up with sediments brought down by the rivers, leaving only narrow passages for the flow of the tide. In this manner were formed the *sea-islands* all along our Southern coast, separated from the mainland only by narrow tidal inlets. These tidal inlets may become filled up, and the whole coast-line transferred farther seaward.

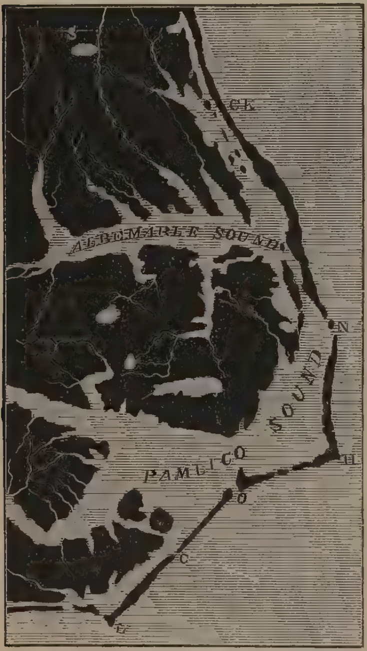

Fig. 34.—Coast of North Carolina.

A large portion of the coasts of the world is thus bordered by wave-formed islands. We have already seen, however, that on some coasts, e. g., Norway, Scotland, etc., islands are formed by the *destructive* action of waves. *Bordering islands*, so common along all coasts, are therefore of two classes, and formed by two opposite effects of waves—

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* See the author's views on this subject, American Journal of Science, vol. xxiii, p. 46, 1857; Nature, vol. xxii, p. 558, 1880; Science, vol. ii, p. 764, 1883.

the one land-destroying, the other land-forming. The islands of one class are high and rocky, of the other low and sandy or muddy; the former are the scattered remains of an old coast-line, the latter the commencing points of a new coast-line.*

SECTION 3.—ICE.

The agency of ice will be considered under the heads of Glaciers and Icebergs; the effects of frost in disintegrating rocks having been already treated of under Atmospheric Agencies. It is only comparatively recently that the great importance of ice as a geological agent has been recognized. To Agassiz is due the credit of having first fully recognized this importance.

Glaciers.—General Principles.

Definition.—In many parts of the earth, where the mountains reach into the region of perpetual snow, and other favoring conditions are present, we find that the mountain-valleys are occupied by masses of compact ice, connected with the snow-cap above, but extending far below the snow-line into the region of cultivated fields, and moving slowly but constantly down the slope of the valley. Such valley-prolongations of the perpetual snow-caps are called *glaciers*. The existence of glaciers and their motion are necessitated by the great *law of circulation*, so universal in Nature. For in those countries where glaciers exist, the waste of perpetual snow by evaporation is small in comparison with the supply by the fall of snow. There would be no limit, therefore, to the accumulation of snow on mountain-tops, if it did not run off, down the slope, by these ice-streams, and thus return into the general circulation of meteoric waters. Glaciers extend not only far below the snow-line, but even far below the mean line of 32°. In the Alps the snow-line is about 9,000 † feet above the sea-level, while some of the glaciers extend down to within 3,225 feet (Prestwich) of the same level, i. e., more than 5,000 feet below the snow-line.

Necessary Conditions.—The conditions necessary to the formation of glaciers are: 1. The mountain must rise into the region of perpetual snow, for the snow-cap is the fountain of glaciers. 2. There must be considerable changes of temperature, and therefore alternate thawings and freezings. This condition seems necessary to the gradual compacting of snow into glacier-ice. The want of this condition is apparently the cause of the non-existence, or small development, of glaciers in tropical regions. 3. A moist atmosphere is favorable to their produc-

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* Coast islands are, however, often formed by subsidence of continental margins.

† Dana's Manual of Geology.

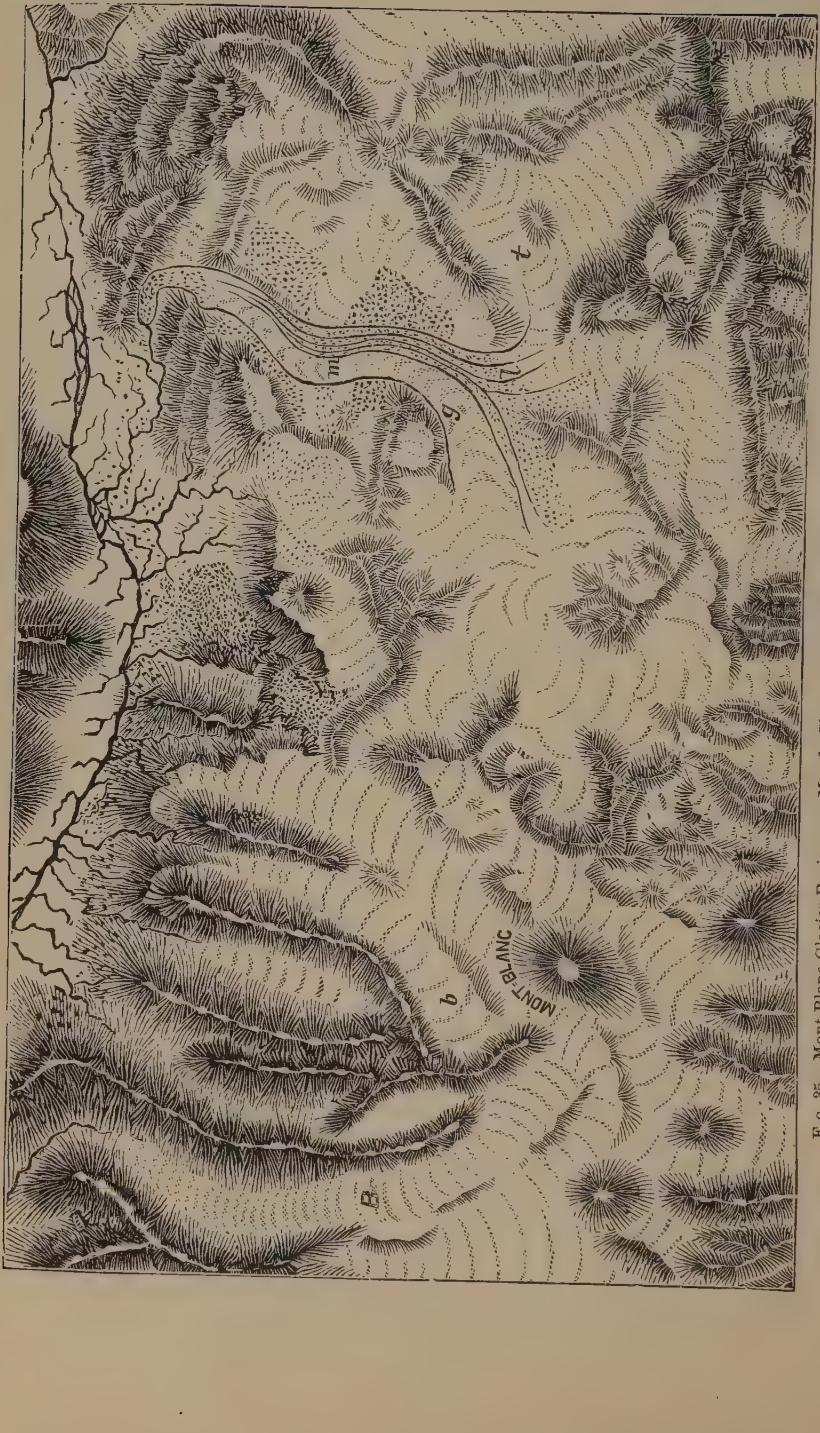

Fig. 35.—Mont Blanc Glacier Region: *m*, Mer de Glace; *g*, Du Géant; *l*, Lechaud; *t*, Talafré; *B*, Bionassay; *b*, Bosson.

tion, for the moister the climate the greater is the snow-fall, and the smaller is the waste by evaporation, and therefore the greater the excess which must run off by glaciers. This is an additional reason why glaciers are not formed under the equator; for the great capacity for moisture of the air in this zone increases the waste while it decreases the fall of snow. This is also the reason of the scanty formation of glaciers in the Sierra Mountains, and their abundance and magnitude in the Alps.

Ramifications of Glaciers.—We have said glaciers are valley-prolongations of the ice-cap. Now, mountain-valleys are of two kinds, viz., 1. The deeper and larger *longitudinal valleys*, between parallel ranges; and, 2. The *transverse* or *radiating valleys*, transverse in case of ridges, and radiating in case of peaks. The longitudinal valleys may be formed either by erosion or by igneous agencies folding the crust of the earth; but the transverse or *radiating valleys are always formed by erosion.* It is these valleys of erosion which are occupied by glaciers. In countries where there are no glaciers they are occupied, of course, by streams. We have already shown (p. 9) how these valleys commence near the top of the mountain as furrows, which, uniting, form gullies, and these, in their turn, forming ravines and gorges, thus becoming less and less numerous, but larger as we approach the base of the mountain. In the same manner, therefore, as streams ramify, so also do glaciers. The only difference is the degree of ramification. Streams ramify almost infinitely, while glaciers seldom have more than three or four tributaries. Fig. 35 is a map of the Mont Blanc glacier region. By inspection of this map it will be seen that the *Mer de Glace*, *m*, receives four tributaries, marked *t*, *l*, *g*, etc. On page 55 is an enlarged view of the same glacier with its tributaries.

Motion of Glaciers.—Again, we have said in our definition that glaciers are in constant motion. By the law of circulation, constant downward motion is as necessary to the idea of a glacier as it is to that of a river, since both the glacier and the river carry away the excess of supply over evaporation. But a glacier, though in constant motion, never passes beyond a certain point, where the slow downward motion is exactly balanced by the melting of the ice by sun and air. This point is called the *lower limit* of the glacier. As long as conditions remain unchanged, the lower end of the glacier remains exactly at the same point, although the substance of the glacier moves always downward. But if external conditions change, the point of the glacier may move upward or downward. There are two opposing conditions which determine the position of the point of the glacier, viz., the *rate of motion* and the rate of melting. Thus, during a succession of cool, damp years, the melting being less rapid, the point of the glacier moves slowly down, sometimes invading cultivated fields and overturning huts, until it finds a new point of equilibrium. During a succession of warm and dry years, on the contrary, the melting being more rapid, the point retreats, to find a new point of equilibrium higher up the mountain. Again, during a cycle of years of heavy snow-fall, the glacier is flooded, its motion increased, and its point advances; while during a cycle of smaller snow-fall its dimensions shrink, its motion is retarded, and its point retreats. But, whether the point be stationary, or advance or recede, the substance of the glacier is ever moving steadily onward. It may be compared to those rivers, in dry, sandy countries, which run ever toward the sea, but never reach beyond a certain point, being absorbed by the sand.

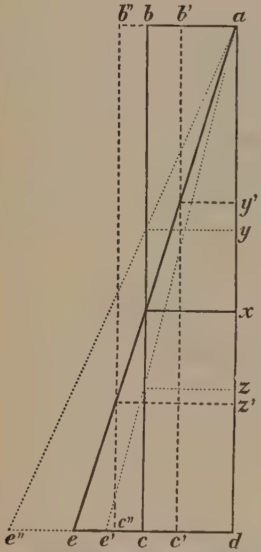

Fig. 36.—Diagram showing the Causes of Advance and Retreat. The dotted lines represent increase and decrease of melting, the broken lines increase and decrease of motion.

Graphic Illustration.—These facts may be graphically represented as follows: Taking first the *motion constant* in time, and the melting variable, let $a\ d$ (Fig. 36) equal the length of the mountain-slope, and the line $a\ b$ ($= c\ d$) the velocity of the glacier-motion taken as uniform. This velocity varies with the slope, as will be seen hereafter, but is little affected by the elevation. It may be taken, therefore, as the same in every part of the slope, and therefore correctly represented by equal lines, i. e., by the ordinates of the parallelogram $a\ b\ c\ d$. The melting power of the sun and air, on the contrary, regularly increases from the top, where it is almost nothing, to the bottom of the mountain. We will, therefore, represent it by the increasing ordinates of the triangle $a\ e\ d$. At x, therefore, where the ordinates of the triangle and of the parallelogram are equal to each other, will be the lower limit of the glacier. During a succession of cool years the rate of melting will be represented by the ordinates of the smaller triangle $a\ e'\ d$, and the point of the glacier will advance to z. During a succession of warm, dry years, the rate of melting will be represented by the larger triangle $a\ e''\ d$, and the point of the glacier will recede to y. Taking next the *melting as constant* in time, and represented as before by the line $a\ e$, and the motion as variable; then, if the rate of motion be represented by ordinates of the line $b\ c$, the point of the glacier will be at x as before. But, during a cycle of glacial flood, the rate of motion is increased and represented by a broken line $b''\ c''$, and the point of equilibrium is advanced to z'; and, during a cycle of diminished snow-fall and shrunken glacier, the rate of motion is represented by $b' c'$, and the point of equilibrium retreats to y'.

Of these two factors of advance and retreat, the second is probably the greatest; for, in the same region and under the same climatic conditions, some glaciers may be advancing and some retreating. The reason is as follows: As in small streams the floods quickly follow the rain, while in long rivers like the Mississippi the flood at the mouth may be delayed a week or ten days; so in short glaciers the ice-flood may reach the point in five or ten years, while in long glaciers it may take fifty or more years.*

Line of the Lower Limit of Glaciers.—We have said, again, that the glacier reaches below the snow-line. There are three lines, or rather *spheroidal surfaces*, running above the surface of the earth, which are apt to be confounded with one another, and must, therefore, be now defined. These are the *line of perpetual snow*, the *mean line of* 32°, and the *line of the lower limit of glaciers.* The line of perpetual snow, at the equator, is about 16,000 to 17,000 feet above the sea-level. As we approach the poles it gradually approaches the sea-level, until it touches at or near the poles, forming thus a spheroid more oblate than the earth itself (Fig. 37). Next follows the mean line of 32°. This commences at the equator, *E*, coincident with the snow-line (it may be even above it—Dana), but diverges as we pass toward the pole, and finally touches the sea-level at about 66° north and south latitude, at *b b*. Below this, again, is the line of lower limit of glaciers, which, commencing again nearly coincident with the two preceding, at the the equator, approaches and touches the sea-level at about 50° latitude, or, under favorable circumstances, at even lower latitudes. The difference between these lines is often several thousand feet. In the Alps, the line of 32° is

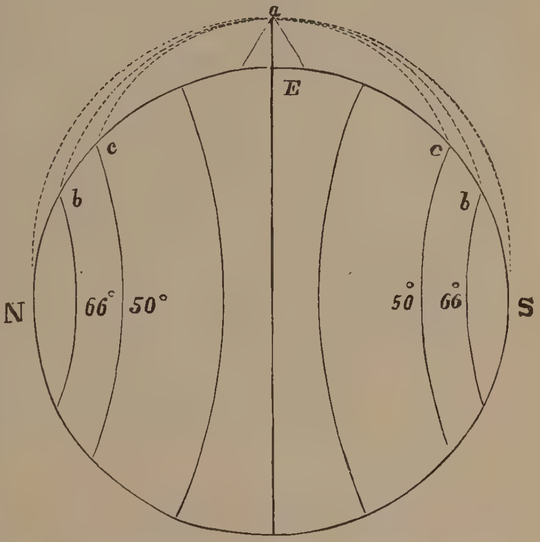

Fig. 37.—General Relation of Limit of Glaciers to Snow-Line.

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* Forel, Archives des Sciences, vol. vi, pp. 5 and 448, 1881.

2,000 feet, and the line of lower limit of glaciers 5,000 feet, below the snow-line. In some parts of the arctic region, the line of 32° is 3,500 feet below the snow-line, and in Norway the lower limit of glaciers is 4,000 feet below the line of 32° (Dana). For the sake of simplicity we have represented the surfaces, of which these lines are the sections, as regular spheroids; but, in fact, they are very irregular, being much influenced by climate. Their intersection with the sea-level will, therefore, not be along lines of latitude, but will be irregular, like isotherms. As the line *a c* marks the lower limit of glaciers in different latitudes, it is evident that at *c* glaciers will touch the sea, and beyond this point will run far into the sea. It is in this manner, as we will see hereafter, that icebergs are formed. In Chili, glaciers touch the sea-level at 46° 40′ south latitude.*

General Description—Glacial Field.—A glacial field may be defined as a perpetual snow-covered area from which flow glaciers in many directions. The field best known is that of the Alps. In the region about Mont Blanc (Fig. 35) and Finsteraarhorn alone there are about 400 glaciers, varying in length from 5 to 15 miles, in width from one half to 3 miles, and in thickness from 200 to 800 feet. In the Himalayas the snow-field is far more extensive and the glaciers much larger —40 miles long and 1,000 feet thick. On the Pacific coast of North America glaciers begin to appear as little isolated glacierets in the Sierra of Middle California, become of respectable size (2½ miles long) on Mount Shasta, almost rival those of the Alps (8 to 10 miles long) on Mount Tacoma, and reach grand proportions, running into the sea and forming icebergs in Alaska. For example, the Muir Glacier is a complex system of ice-streams altogether more than 100 miles long. The Malaspina Glacier is a great Mer de Glace, covering an area of 1,500 square miles, fed by many ice-streams coming down from the Mount St. Elias group.

Continental Ice-Sheet.—But it is only in arctic and antarctic regions that we find ice action on a scale which gives us any adequate idea of its agency in the Glacial period. *Greenland* is a continental mass 1,200 miles long and 600 miles wide. This whole area of 600,000 square miles is buried 2,000 to 3,000 feet deep under a continuous mass of snow and ice which moves bodily with slow glacier motion seaward in all directions, and finally through the great fiords into the sea to form icebergs. The antarctic ice-sheet is much larger; it covers an area of 4,000,000 to 8,000,000 square miles to a supposed depth of 10,000 feet. This great mass moves in all directions with slow glacial motion, and runs out many miles to sea to break off there and form icebergs.

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* D'Archiac, Histoire de Géologie.

An Individual Glacier.—A typical glacier may be divided into two parts: a great amphitheatral part in which the snows are gathered; and an icy tongue or glacier proper, which runs from the amphitheater or *cirque* down the valley. Or we may regard water as existing in four conditions: first, as light snow; then, as we go down, as *névé* or granular snow—half snow, half ice; then as solid glacier ice; and, finally, as a river. The river which flows from the snout of every glacier is formed partly by the natural drainage of the hydrographical basin, but mainly by the melting of the glacier by sun and air. The thickness removed (ablation) during a single summer is 18 to 25 feet. The surface of a glacier is therefore covered with rushing rills. These do not run the whole length, but soon fall into crevasses, find their way to the bottom, and generally come out beneath the snout of the glacier.

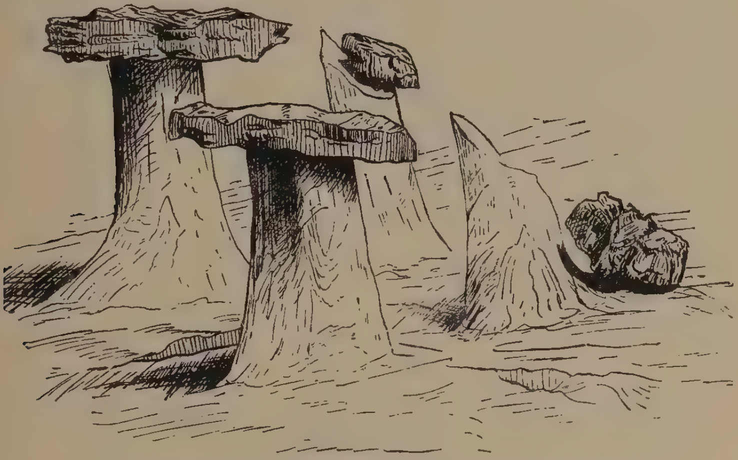

Fig. 38.—Ice-Pillars on Parker Creek Glacier, California (after Russell).

We are apt to suppose that the surface of a glacier must be smooth. This is, however, very far from being true. On the contrary, the extreme *roughness* of the ice-surface renders the ascent along the glacier extremely difficult. This inequality of surface is due partly to unequal melting and partly to *crevasses*, or fissures. The unequal melting is produced as follows: A stone, lying on the surface of a glacier, protects the surface beneath from the rays of the sun. Meanwhile the surrounding ice is melted, until finally the slab of stone stands on a column of ice often several feet in height (Fig. 38). A slab seen by Forbes measured 23 feet long, 17 feet wide, and 3½ feet thick, and rested on a column 13 feet high. In such cases the stone finally falls off, leaving a sharp pinnacle, and another column commences to form under the stone. In this manner are formed what are called *needles.* When we consider that there are immense numbers of stones on the glacier-surface, we can easily see that these needles will multiply indefinitely. If, on the other hand, a *thin* stratum of earth stains the surface of the glacier in spots, these spots will melt *faster* than the surrounding ice, because more absorbent of heat, and thus form deep holes.

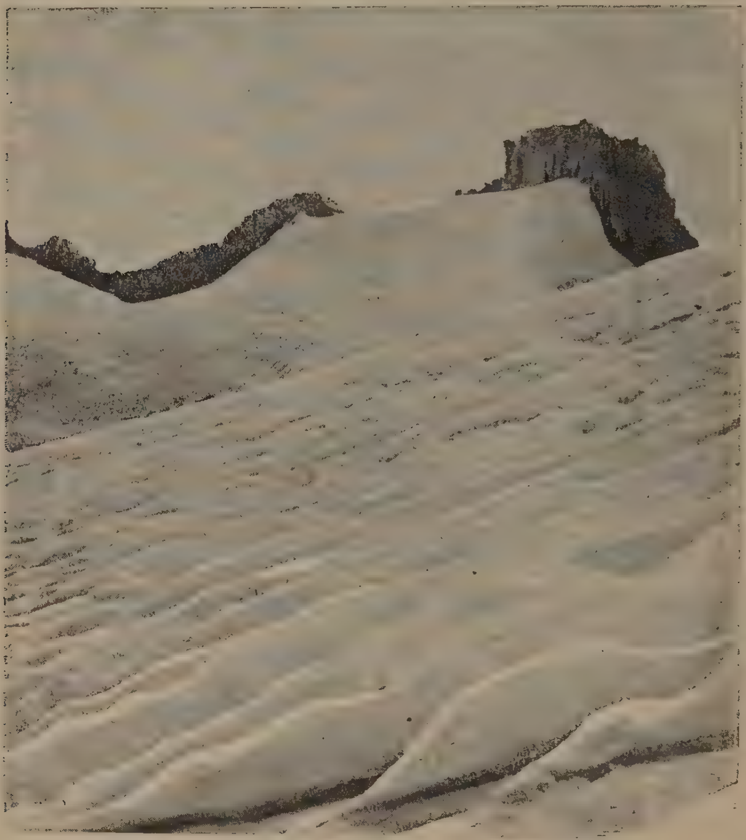
FIG. 39.—Ice-Blades on Hallet Glacier, Mummy Mountain, Colorado (from Photograph by Chapin).

An admirable illustration of extreme inequality of the surface of ice is seen in the case of the small residual glacier still remaining on Mount Lyell, Sierra Nevada.* On the top of Mount Lyell there is an immense amphitheater (*cirque*), filled with snow and ice. In August the surface of this ice-field is set with ice-blades, three to four feet high and only two feet apart, as shown in Fig. 39. They are probably formed as follows: In winter, when the snow is deep and light, it is blown into wind-ripples on a large scale. These soon become fixed by surface melting and freezing, and then the greater action of the sun in the troughs, partly by the reverberation of heat and partly by accumulation of dust there, causes these to become deeper and deeper. It is necessary to remember that there is little snow or rain in this region after about the first of May until November.

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* See paper by the writer, American Journal of Science, vol. v, p. 333, 1873.

Again, fissures or crevasses, often of great size, ten to twenty feet wide, one hundred feet deep, and sometimes running entirely across the glacier, are very abundant. As the surface of the glacier is often covered with snow, and the fissures thus concealed, they form the most dangerous feature connected with Alpine travel. The law which governs their formation will be discussed hereafter; suffice it to say that the great transverse fissures are formed by the glacier passing over an angle formed by a sudden change in the slope of the bed. Streams, produced by the melting of ice, running on the surface of the glacier, plunge into these fissures with a thundering noise, and hollow out immense wells, called *moulins*, and magnificent *ice-caves*. Although the glacier moves, the great crevasses and the wells with their falls remain *stationary*, precisely as the position of a rapid or breaker remains stationary, although the river runs onward; and for the same reason, viz., that it is reformed always on the same spot.

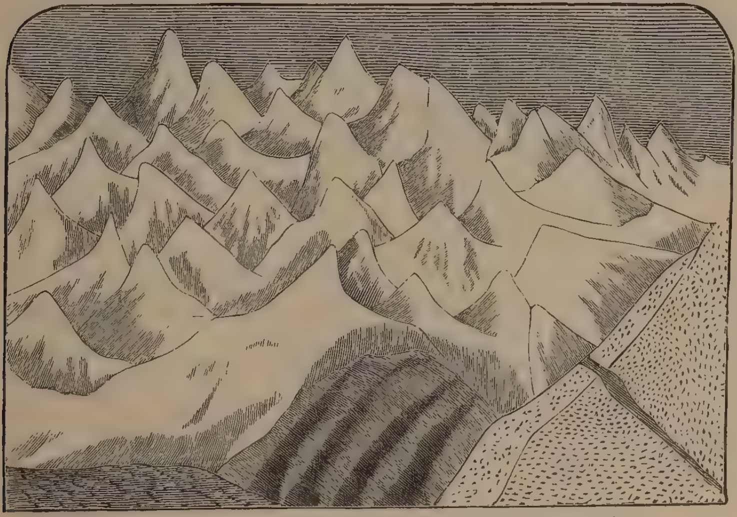
FIG. 40.—Inequalities of the Surface of a Glacier (after Agassiz).

From all these causes the surface of a glacier is often studded over with conical masses and projecting points of every conceivable shape. This is well shown in the accompanying figure (Fig. 40). These inequalities are, of course, the result of *differential* melting. The whole melting (ablation) is much greater, even as much as twenty-five feet in the course of the summer.*

Earth and Stones, etc.—The surface of a glacier is, morever, largely covered with earth and stones gathered in its course from the crumbling cliffs on either side. These are often so abundant as almost to cover the surface. More usually, however, they are distributed in two or more rows, called *moraines*. Fig. 41 is a view of a glacier, with its moraines and lateral crevasses.

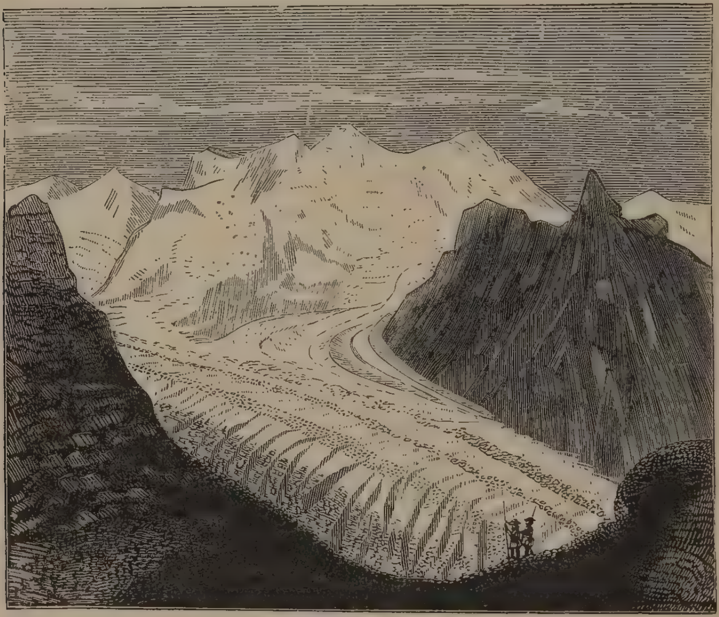

Fig. 41.—Zermatt Glacier (Agassiz).

Such is a general description of the appearance of a glacier. There are, however, several points which, by their importance and interest, require special notice. These are: 1. *Moraines*; 2. *Glaciers as a geological agent*; 3. *Glacier-motion*; and 4. *Glacier-structure.*

Moraines.

There are four kinds of moraines described by writers, viz., *lateral* moraines, *medial* moraines, *terminal* moraines, and *ground* moraines. *Lateral moraines* are continuous lines of earth and stones, arranged on either margin of the glacier and evidently formed from the ruins of the crumbling cliffs of the inclosing valley. This *débris* does not fall from every part of the valley-sides, but generally only from certain bold, projecting cliffs. It is converted into a continuous line by the motion of the glacier, just as light materials thrown constantly into a river at one point would appear as a continuous line on the stream.

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* Prestwich, Geology, vol. i, p. 176.

Medial moraines are similar lines of *débris*, occupying the central portions of the glacier. Sometimes there is but one; sometimes two, or more; sometimes the whole surface of the glacier is almost covered with them. The true explanation was first pointed out by Agassiz. They are formed by the coalescence of the *interior* lateral moraines of *tributary* glaciers, carried down the main trunk by the motion of the ice-current. The accompanying map (Fig. 42) of the Mer de Glace and its tributaries shows clearly the manner in which these moraines are formed. Both lateral and medial moraines are generally situated on a ridge of ice, sometimes fifty to eighty feet high, evidently formed by the protection of the ice, in this part, from the melting power of the sun. The fragments of rock brought down by glaciers are often of enormous size. One described by Forbes contained 244,000 cubic feet.

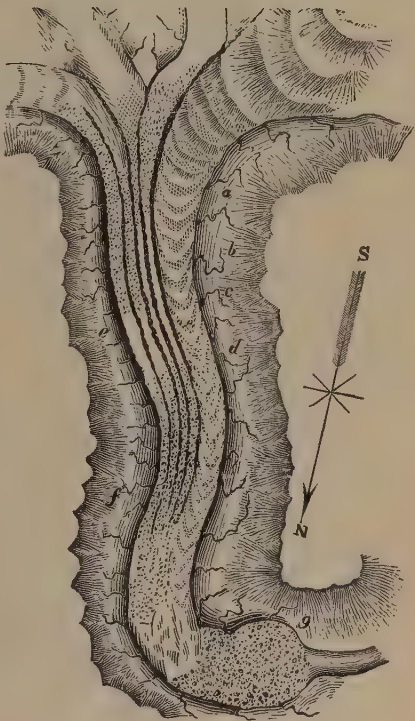

FIG. 42.—Mer de Glace.

The *ground* moraine is the mass of *débris* carried between the glacier and its bed. It is derived partly from erosion of the bed, and partly from top material (lateral and medial moraines) ingulfed and carried down to the bottom.

Everything which falls upon the surface of the glacier is slowly and silently carried downward by this ice-stream, and finally dropped at its point. Much finely-triturated matter is also pushed along beneath the glacier, and finds its way to the same point. In the course of time an immense accumulation is formed, of somewhat crescentic shape, as seen in Fig. 42.

This accumulation is called the *terminal moraine.* It is the *delta* of this ice-river. The existence of moraines is a constant witness of the motion of the glaciers.

Glaciers as a Geological Agent.

Glaciers, like rivers, *erode* the surface over which they move, *carry* the materials gathered in their course often to great distances, and finally *deposit* them. In all these respects, however, the effects of their action are perfectly characteristic.

Erosion.—When we consider the weight of glaciers and their unyielding nature as compared with water, it is easy to see that their erosive power must be very great. This is increased immensely by fragments of stone of every conceivable size carried along between the glacier and its bed. These partly fall in at the sides and become jammed between the glacier and the confining rocks, partly fall into crevasses and work their way to the bed, and partly are torn from the rocky bed itself. But on the other hand, on account of their slow motion, glacier-erosion is by force of *pressure*, while that of water is by force of *impact.* The effects of glacier-erosion differ entirely from those of water: 1. Water, by virtue of its perfect fluidity, wears away the softer spots of rock, and leaves the harder standing in relief; while a glacier, like an unyielding rubber, grinds both hard and soft to one level. This, however, is not so absolutely true of glaciers as might be

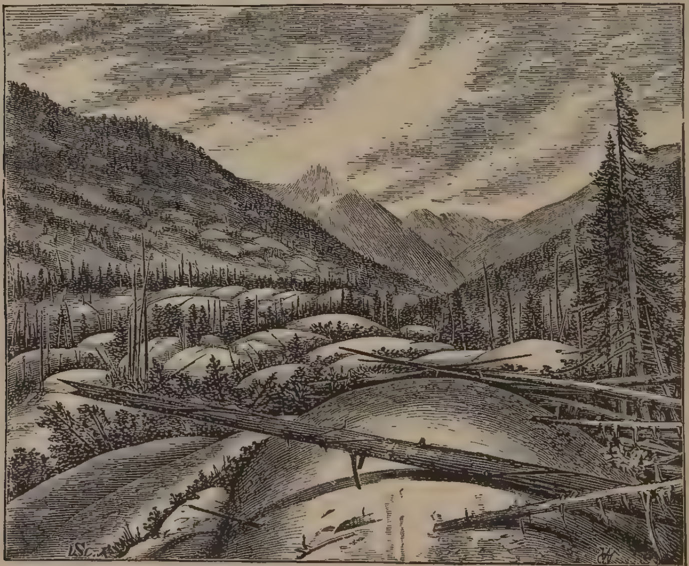

Fig. 43.—Roches Moutonnées of an Ancient Glacier, Colorado (after Hayden).

supposed. Glaciers, for reasons to be discussed hereafter, conform to large and gentle inequalities of their beds, though not to small ones, acting thus like a very *stiffly viscous* body. Thus their beds are worn into very remarkable and characteristic smooth and rounded depressions and elevations called *roches moutonnées* (Fig. 43). Sometimes *large and deep hollows* are swept out by a glacier at some point where the rock is softer or where the slope of the bed changes suddenly from a greater to a less angle. If the glacier should subsequently retire, water accumulates in these excavations and forms lakelets. Such lakelets are common in old glacial beds.

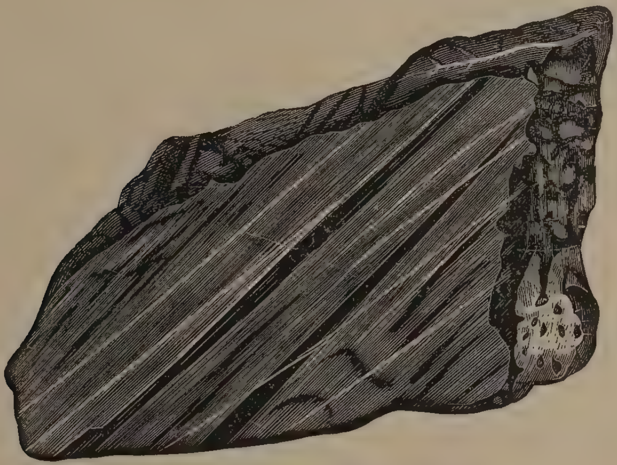

Fig. 44.—Glacial Scorings (after Agassiz).

2. The *lines* produced by water-erosion, if detectible at all, are always more or less irregular and meandering; while those produced by glaciers are *straight* and *parallel* (Fig. 44).

Thus, smooth, gently-billowy surfaces, marked with straight, parallel scratches, are very characteristic of glacial action. We will call such surfaces *glaciated*, and the process *glaciation*.

3. The turbidity of ordinary rivers is usually yellowish, the turbidity of glacial rivers is always *milky*. The one is due to sediments derived from soil, and therefore oxidized; the other is due to ground-up sound rock or *rock-meal*.

Transportation.—The transporting power of glaciers follows no law similar to that pointed out under rivers—in fact, it has no relation at all to velocity. The reason is, that the stone rests on the surface as a *floating body*. There is, therefore, no limit to the transporting power. Bowlders of 250,000 cubic feet are carried with the same ease and the same velocity as the finest dust.

Deposit—Balanced Stones.—A water-current carrying stones bruises and rounds their corners, and deposits them always in the most *secure* positions; but glaciers often deposit huge *angular* fragments of rock in the most *insecure* positions—so nicely balanced, sometimes, that a touch of the hand will dislodge them. The reason is, they are set down by the gradually melting ice with inconceivable gentleness. Thus balanced stones, rocking-stones, etc., are common in glacial regions. In using these as a sign of glacial action, however, we must recollect that a bowlder dropped by any agent, or even a bowlder of disintegration (p. 6), may in time become a rocking-stone, by slow but irregular disintegration changing the position of the center of gravity. But *angular erratics* in insecure positions are very characteristic of glacial action.

Material of the Terminal Moraine.—The material of the terminal moraine is very characteristic: 1. It consists of fragments of every conceivable size, from huge bowlders down to fine earth, mixed together into an heterogeneous mass entirely different from the neatly-sorted deposits from water. It is, therefore, entirely *unsorted and unstratified*, and without organic remains. 2. The mass consists of two parts, viz., that which is carried on the top of the glacier, and that which was forced out beneath (*ground moraine*). The first consists of loose material containing angular, unworn fragments; the other of fine compact material containing fragments worn and polished, and scratched with straight, parallel scratches, but in both cases entirely different from *water-worn* pebbles. In all respects, therefore, the action of glaciers is characteristic and can not be confounded with that of water.

Evidences of Former Extension of Glaciers.—It is by evidence of this kind that the former great extension of glaciers in regions where they now exist, and the former existence of glaciers in regions where they no longer exist, have been proved. We have already stated that during a succession of cool, damp seasons, a glacier may extend far beyond its previous limits. Similar changes take place also in the depth of a glacier. In a word, glaciers are subject to floods like rivers; only these floods, instead of being annual, are *secular*. Now, as rivers after floods leave floating material stranded on the banks, showing the height of the flood-water, so, in the decrease of a glacier, lines of bowlders are left stranded, often delicately balanced, on ledges high up the sides of the valley. These lines of bowlders mark the former height of the glacier. Some of these lines have been found in the Alps 2,000 feet above the present

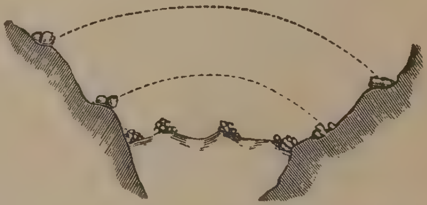

FIG. 45.—Section across Glacial Valley, showing old Lateral Moraines.

level. Fig. 45 is a cross-section of a glacial valley. The dotted lines show the former level. In the same valleys we find old terminal moraines (Fig. 46, a') miles beyond the present limit of the glacier. The characteristic planing, polishing, and parallel scoring, have been found equally far above the present level and beyond the present limit of Alpine glaciers.

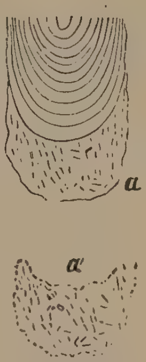

Fig. 46—Old Terminal Moraines.

Glacial Lakes.—When a glacier retreats, the water of the river which flows from its point may accumulate in great *rock-basins* scooped out by the glacier, or else behind the old terminal moraines. In these two ways lakes are often formed.

Motion of Glaciers and its Laws.

Evidences of Motion.—That glaciers move slowly down their valleys was long known to Alpine hunters. Rude experiments of the first scientific explorers confirmed this popular notion. Hugi in 1827 built a hut upon the Aar glacier. This hut was visited from year to year by scientific explorers and its change of position measured. In 1841 Agassiz found that it had moved 1,428 metres in fourteen years, or about 100 metres (330 feet) per annum. The ruins of Agassiz's hut (Hôtel Neuchatelois), built in 1840, were found in 1884. They had moved in forty-four years 7,900 feet.* Numerous other observations from year to year by Agassiz and others, on the position of conspicuous bowlders lying on the surface of glaciers, confirmed these results and placed the fact of glacier-motion beyond doubt. But the most important observations determining both the *rate* and the *laws* of glacier-motion were made in 1842 by Prof. Agassiz on the Aar glacier, and Prof. Forbes on the Mer de Glace. By these experiments, carefully made by driving stakes into the glacier, in a straight row from one side to the other, and observing the change in the relative position of the stakes, it was determined that the center of the glacier moved faster than the margins. This *differential* motion is the capital discovery in relation to the motion of glaciers. It is claimed by both Agassiz and Forbes. It had, however, been previously distinctly stated, though not proved, by Bishop Rendu.

Laws of Glacier-Motion.—The term *differential motion* is a condensed expression for all the laws of glacier-motion. It asserts that the different parts of a glacier do not move together as a solid, but *move among themselves in the manner of a fluid.* A glacier moves like a fluid, though a very stiff, *viscous* fluid ; its motion may therefore be rightly called *viscoid*. We will mention some of the most important laws of fluid-motion, and show that glaciers conform to them:

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* Nature, vol. xxx, p. 477, 1884.

1. *The Velocity of the Central Parts is greater than that of the Margins.*—This well-known law of currents, the result of friction of the fluid against the containing banks, was completely proved in the case of glaciers by the experiments of Agassiz and Forbes, and recently confirmed in the most perfect manner by Tyndall. A line of stakes, *a b c d e f g*, placed in a straight row across a glacier, becomes every day more and more curved, as seen in Fig. 47. The exact rate of motion for each stake is easily measured by the theodolite. The rate of the center is often many times greater than that of the margins.

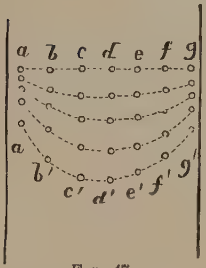

Fig. 47.

2. *The Velocity of the Surface is greater than that of the Bottom.*—This law of currents, which is the necessary result of friction on the bed, is more difficult to prove in the case of glaciers, because it is difficult to get a vertical section. The necessary observation was, however, successfully accomplished by Prof. Tyndall in 1857. We have already said (page 57) that glaciers conform to large but not to small inequalities of their channels; a glacier, therefore, passing by a narrow side-ravine will expose its whole thickness on the side. Prof. Tyndall, having found such a side exposure more than 140 feet vertical, placed three pegs in a vertical line, one near the top, one near the middle, and one at the bottom (Fig. 48, *a b c*). The vertical line became *more and more inclined* daily. The daily motion at top was six inches, in the middle 4·5 inches, and at the bottom 2·5 inches. Thus, glaciers, like rivers, slide on their beds and banks, producing erosion; but, also, the several layers, both horizontal and vertical, slide on each other.

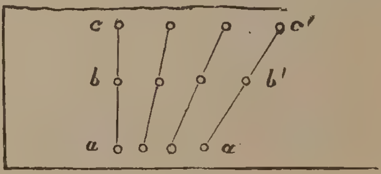

Fig. 48.

3. *The Velocity increases with the Slope.*—Fig. 49 represents the surface-slope of the glacier *Du Géant*, *G;* the *Mer de Glace*, *M;* and the glacier *De Bois*, *B;* and their daily motion. The increase of velocity with the slope is evident.

4. *The Velocity increases with the Fluidity.*—The daily motion of glaciers is greater in summer, when the ice is rapidly melting, than in winter; and in mid-day than at night.

5. *The Velocity increases with the Depth.*—In the Alps, where the thickness is 200 to 300 feet, the mean daily motion is one to three feet; but in Greenland, where the thickness is 2,000 to 3,000 feet, the daily

motion, in spite of the much lower temperature, is in some cases 60 feet* or even 99 feet.† The Muir Glacier in Alaska, according to Wright, moves 70 feet a day; but the later results of Ried make it only 7 to 10 feet.‡

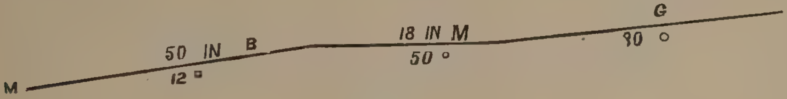

FIG. 49.

6. *Fluid Currents conform to the Irregularities of their Channel.*—Glaciers, like water-currents, conform to the inequalities of the bottom and sides of their channels. They have their shallows and their deeps, their narrows and their lakes, their cascades, their rapids, and their tranquil portions. Fig. 50 shows a glacier running through a narrow gorge into a wide lake of ice, and again through another gorge. There is this difference, however, between a glacier and a water-current, viz., that, while the latter conforms to even the *minutest and sharpest* outlines, the former conforms only to the *larger or more gentle.* In this, a glacier acts like a stiff, viscous fluid.

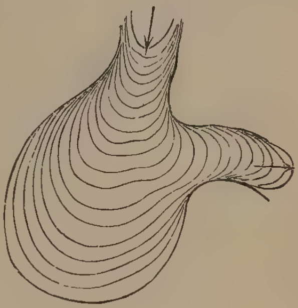

FIG. 50.

7. *The Line of Swiftest Motion is more sinuous than the Channel.*—We have already seen that this is true of rivers (page 24). The line of swiftest current is reflected from side to side, increasing the curves by erosion. The same has been proved by Tyndall to be the case with glaciers. Fig. 51 represents a portion of a sinuous glacier, like the Mer de Glace: the dotted line represents the line of swiftest motion.

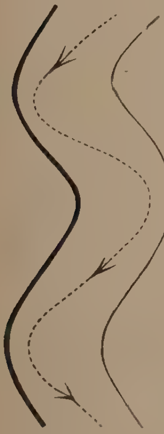

FIG. 51.

8. Partial currents up and down and side to side by inequalities.

Theories of Glacier Motion.

There are few subjects connected with the physics of the earth which have excited more interest than that of glacier-motion. The subject is one of exceeding beauty, and not without geological importance. Passing over several very ingenious theories which have now been abandoned, the first theory which was conceived in the true inductive spirit, and which explains the differential motion, is that of Prof. James Forbes.

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* Helland, Journal of Geological Society, vol. xxxiii, p. 142 *et seq.*

† Science, vol. xi, p. 259, 1888.

‡ American Geologist, vol. ii, p. 276, 1893.

Viscosity Theory of Forbes.

Statement of the Theory.—According to Forbes, ice, though apparently so hard and solid, is really, to a slight extent, a viscous body. In small masses this property is not noticeable, but in large masses and under long-continued pressure it slowly yields, and will flow like a stiffly viscous fluid. In large masses like a glacier, this steady, powerful pressure is furnished by the immense weight of the superincumbent ice.

Argument.—It is evident that this theory completely accounts for all the phenomena of glacier motion, even in their minutest details. A glacier, beyond all doubt, moves *like* a viscous body, but it is still a question whether it does so by virtue of a property of viscosity. The proposition that ice is a viscous substance seems at first palpably absurd. It is necessary, therefore, to show that this proposition is not so absurd as it seems.

The properties of solidity and liquidity, though perfectly distinct and even incompatible in our minds, nevertheless, in Nature, shade into one another in the most imperceptible manner. *Malleability*, *plasticity*, and *viscosity* are intermediate terms of a connecting series. The idea which underlies all these expressions is that of *capacity of motion of the molecules among themselves without rupture:* the difference among them being the greater or less resistance to that motion. In the case of malleable bodies, like the metals, great force is required to produce motion; in plastic bodies, like wax or clay, less force is required; in viscous bodies, like stiff tar, motion takes place spontaneously but slowly; while in liquids it takes place freely and with little or no resistance. In all these cases, if the pressure be sufficient, the body will change its form without rupture—in other words, will *flow.* Now, by increasing the mass we may increase the pressure to any extent. Therefore, all malleable, ductile, plastic, or viscous bodies, if in sufficiently large masses, will flow like water. Thus, a mass of lead, sufficiently thick, would certainly flow under the pressure of its own weight.

But solid bodies may be divided into two great classes, viz., bodies which are malleable, plastic, or viscous, and bodies which are *brittle;* the very idea of brittleness being that of total incapacity of motion among the particles without rupture. Now, ice belongs to the class of brittle bodies. Forbes attempts to remove this difficulty by showing that many apparently brittle bodies will also flow under their own weight; for instance, pitch, so hard and brittle that it flies to pieces under a blow of the hammer, will, if the containing barrel be removed, flow and spread itself in every direction. So, also, molasses-candy, made quite hard and brittle, will still flow by standing. A remarkable pitch-lake, about three miles in circumference, occurs in Trinidad. The pitch is described as in constant, slow-boiling motion, coming up in the center, flowing over to the circumference, and again sinking down. Yet this pitch in small masses, would be called solid and brittle. Struck with a hammer, it flies to pieces like glass. In fact, the essential peculiarity of a stiff, viscous body, in which it differs from malleable or plastic bodies, is, that it yields *only* to *slowly-applied force.*

Forbes, therefore, thinks that glacier-ice is an exceedingly stiff, viscous substance, which, though apparently brittle in small quantities and to sudden force, yet, under the slow-acting but powerful pressure of its own weight, flows down the slope of its bed, squeezing through narrows and spreading out into lakes, conforming to all the larger and gentler inequalities of bed and banks, but not to the sharper ones. The velocity of motion is small in the same proportion as the viscous mass is stiff. The descent of the Mer de Glace from the cascade of the Glacier du Géant to the point of Glacier de Bois, a distance of ten miles, is 4,000 feet. Water, under these circumstances, would rush with fearful velocity. The glacier moves but two feet in twenty-four hours.

Such viscosity of ice as supposed by Forbes is now proved by experiments. Ice-boards supported at the two ends bend into an arc under their own weight. Cylinders of snow compacted into ice may be bent in the hand to a semicircle without rupture,* and bars of ice may even be stretched by slow pulling.†

Regelation Theory of Tyndall.

If ice be indeed a viscous body, then there seems no reason why it should not yield to pressure even in small masses, if the pressure be sufficiently slowly graduated. In the hands of a skillful experimentalist it ought to exhibit this property. Prof. Tyndall tried the experiment. Masses of ice of various forms were subjected to slowly-graduated, hydrostatic pressure. In every case, however slowly graduated the pressure, the ice broke; but if the broken fragments were pressed together, they reunited into new forms. In this manner, ice in the hands of Prof. Tyndall proved as plastic as clay: spheres of ice (*a*, Fig. 52) were flattened into lenses (*b*), hemispheres (*c*) were changed into bowls (*d*), and bars (*e*) into semi-rings (*f*). He even asserts that ice may be molded into any desirable form; e. g., into vases, statuettes, rings, coils, knots, etc. Here, then, we have a power of being molded such as was not dreamed of before; but this power was not dependent on a property of viscosity, but upon another property long known, but only recently investigated by Faraday, viz., the property of *regelation*.

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* Aitkin, American Journal of Science, vol. v, p. 305, third series, 1873.

† American Journal of Science, vol. xxxiv, p. 149, 1887; and Nature, vol. xxxix, p. 203, 1888.

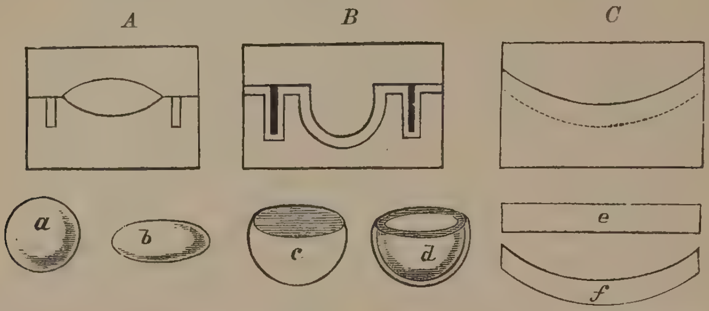

FIG. 52.—*A B C*, molds; *a c e*, original forms of the ice; *b d f*, the forms into which they were molded.

Regelation.—If two slabs of ice be laid one atop of the other, they soon freeze into a solid mass. This will take place not only in cold weather, but in midsummer, or even if boiling water be thrown over the slabs. If a mass of ice be broken to pieces, and the fragments be pressed or even brought in contact with one another, they will quickly unite into a solid mass. Snow pressed in the warm hand, though constantly melting, gradually becomes compacted into solid ice. This very remarkable but imperfectly understood property of ice completely explains the phenomena of molding ice by experiment. By this property the broken fragments reunite in a new form as solid as before. We may possibly call this property of molding under pressure *plasticity* (although it is not true plasticity, since it does not mold without rupture, but by *rupture and regelation*); but it can not in any sense be called *viscosity*, for the true definition of viscosity is the property of *yielding under tension*—the property of *stretching* like molasses-candy, or melted glass; but ice in the experiments, according to Tyndall, did not yield in the slightest degree to tension. In the experiment, if, instead of placing the straight bar at once into the curved mold, it had been placed successively in a thousand molds, with gradually-increased curvature, or, still better, if placed in a straight mold, and this mold, while under pressure, curved slowly, then there would have been no sudden visible ruptures, but an infinite number of small ruptures and regelations going on all the time. *The ice would have behaved precisely like a viscous body.* Now, this is precisely what takes place in a glacier.

Application to Glaciers.—A glacier, on account of its immense mass, is, *in its lower parts*, under the heavy pressure of its own weight tending to mold it to the inequalities of its own bed, and *in every part* under a still more powerful pressure—a pressure proportioned to the height of the head of the glacier—urging it down the slope of its bed. Under the influence of this pressure the mass is continually yielding by fracture of all sizes, but, after changing the position of its parts, again uniting by regelation. By this constant process of *crushing*, *change of form*, and *reunion*, the glacier behaves like a plastic or viscous body; though of true plasticity or true viscosity there is, according to Tyndall, none. In fact, we have in the phenomena of glaciers the most delicate test of viscosity conceivable; but we find the glaciers will not stand the test. For instance, the slope of the Mer de Glace at one point changes from 4° to 9° 25′ * (Fig. 53), and yet the glacier, although moving but two feet a day, can not make this slight bend without rupture; for at this point there are always large transverse fissures which heal up below by pressure and regelation. In another place the glacier is similarly broken by passing an angle produced by a change of slope of only 2°. It seems almost impossible that a body having the slightest viscosity should be fractured under these circumstances. Tyndall concludes, therefore, that the motion of glaciers is *viscoid*, but the body is *not viscous*—the viscoid motion being the result, not of the property of viscosity, but of fracture, change of position, and regelation.

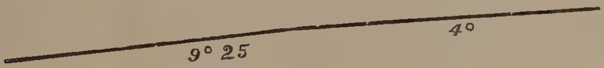

Fig. 53.

Comparison of the Two Theories.—Forbes's theory supposes motion among the *ultimate* particles, *without rupture.* Tyndall's supposes motion among *discrete* particles *by rupture*, *change of position*, *and regelation.* The undoubted viscoid motion is equally explained by both: by the one, by a property of *viscosity;* by the other, by a property of *regelation.* There can be little doubt that both views are true, and that both properties are concerned in glacial motion.

Recent Theories.

Croll's Theory.—Croll has recently, in his work on Climate and Time, brought forward a theory which has attracted much attention. Moseley had previously attempted to prove the untenableness of all theories attributing the motion of glaciers to gravity, by showing experimentally that the *shearing force of ice* (the force necessary to slide one layer on another, as in differential motion) is many times greater than that portion of gravity which acts in the direction of the slope of a glacial bed. Croll, accepting Moseley's view in regard to the shearing force of ice, but accepting also gravity as the moving force of glaciers, thinks to reconcile these by supposing that there is in ice, when subjected to heat, a *momentary* loss of cohesion by melting, which is *transferred from molecule to molecule*, giving rise thereby to a kind of intestine molecular motion similar in its effects to viscosity. The process is as follows: Heat falling on glacier-ice melts its surface. The water thus formed runs down to a lower level, and is again refrozen. Now, what takes place *conspicuously* on the surface takes place *molecularly* in the interior of the ice. In every part the ice-molecules are melting and refreezing. A molecule takes up heat by melting, runs down to an infinitesimally lower point, refreezes, and in so doing gives up its heat and melts another molecule, which in its turn seeks a lower position, and, by refreezing, transfers its heat and fusion to still another molecule, and so on. Thus the whole glacier is in a state of molecular movement downward.

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* Tyndall, Glaciers of the Alps.

The theory is ingenious, but somewhat obscure. We will, therefore, dismiss it with two remarks: 1. Moseley's objection to gravity as the moving force of glaciers is invalidated by the fact that he does not take sufficiently into account the effect of *time* and *slowly-applied pressure* in determining shearing; and *in stiffly viscous substances time is the controlling element.* 2. Until we understand better than we now do the actual behavior of ice-molecules in glacial motion, Croll's theory must be regarded only as a modification (though, perhaps, an important modification) of Forbes's; for it supposes a *molecular differential* motion determined by gravity, and into which both heat and time enter as elements. It is an attempted *physical explanation of the viscosity of ice.*

Thomson's Theory.—Some time ago James Thomson brought forward a theory which deserves far more attention than it has yet received. Thomson shows that the fusing-point of ice is *lowered*, and, therefore, that ice at or near its fusing-point (as is the fact in glaciers) is *promptly melted by pressure.* Now, it is obvious that, in the differential motion of glaciers, whatever point at any moment receives the greatest stress of pressure must melt and give way, and, the stress being relieved, it must immediately again refreeze. Meantime, by change of relative position of parts, the stress is transferred to some other point, which in its turn melts, gives way, is refrozen, and transfers its stress to still another point, and so on. If we compare this theory with Tyndall's, in both cases the ice gives way at the point of greatest stress—in the one case stress of tension, in the other of pressure—in the one case *by fracture*, in the other *by melting.* Differential motion, therefore, in the one case is by *fracture, change of position, and regelation;* in the other by *melting, change of position, and regelation.**

Structure of Glaciers.

There are two points connected with the structure of glaciers which require notice, viz., the *veined structure* and the *fissures.*

Veined Structure.—The ice of glaciers is not homogeneous, but consists of white vesicular ice (white because vesicular), banded, often very beautifully, with solid transparent blue ice (transparent blue because solid), the banding sometimes so delicate that a hand-specimen looks like striped agate. These *blue veins* are not continuous planes, but apparently very *flat lenticular* in shape, varying in thickness from a line to several inches, and in length from a few inches to several feet. Their direction being parallel to one another, they give a stratified or cleavage structure to the glacier, and, in melting, the glacier often splits or cleaves along these planes. According to Prof. Forbes, looking upon the glacier as a whole, we may regard the strata as taking the form represented by the subjoined figures. In a section parallel to the surface (Fig. 54, *a*), the strata outcrop in the form of loops. A cross-section (Fig. 54, *b*) shows them lying in troughs, and a longitudinal vertical section (Fig. 54, *c*) shows the manner in which they

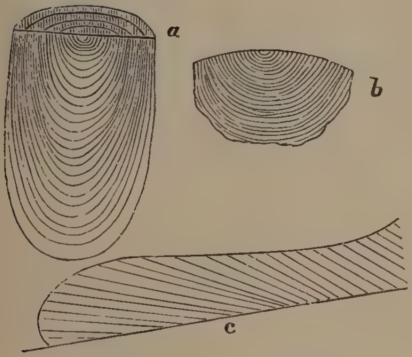

FIG. 54.—Sections of a Glacier.

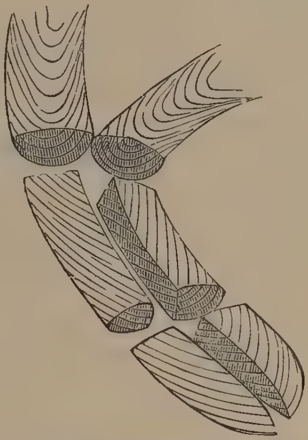

FIG. 55.—Ideal Diagram, showing Structure of Glaciers (after Forbes).

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* Recent experiments by Mügge (Jour. Geol., vol. iii, p. 966) seem to prove that the apparent viscosity of glaciers is the result of shearing along the cleavage planes of the crystalline granules of the glacier-ice.

dip. Fig. 55 is an ideal glacier cut in several directions, and combining in one view the three sections given above. It is generally impossible to trace the veins around from side to side. Sometimes they are most distinct on the margins, and then are called *marginal veins;* sometimes at the point of the loop—*transverse veins;* sometimes tributaries running together, as in the figure (Fig. 55)—the interior branches of the two loops coalesce, and are flattened against one another, and form *longitudinal veins.*

Fissures.—These are also *marginal*, *transverse*, and *longitudinal.* The marginal fissures are shown in Fig. 41; they are always at right angles to the marginal veins.

Theories of Structure.

Fissures.—There can be no doubt that the great fissures or crevasses are produced by *tension* or *stretching*, and that their direction is always at right angles to the line of greatest tension. Thus the *transverse* fissures are produced by the stretching of the glacier in passing over a salient angle. The *marginal* fissures are produced by the dragging or pulling of the swifter central portions upon the slower marginal portions. It has been proved by Hopkins, the English physicist and geologist, that the line of greatest tension from this cause would be inclined 45°, with the course of the glacier as shown by the arrows (Fig. 56).

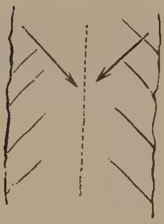

Fig. 56.

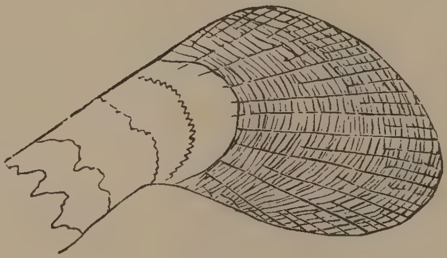

Fig. 57.

The fissures should be at right angles to these lines, and, therefore, also inclined 45° with the margin, and running upward and inward. The longitudinal fissures are best seen where a glacier runs through a narrow gorge out on an open plain. The *lateral* spreading of the glacier causes it to crack longitudinally (Fig. 57). Fig. 58 is a longitudinal vertical section of the same.

Veined Structure.—Tyndall has shown conclusively that veins are always at right angles to the line of greatest pressure, and that, therefore, they are produced by *pressure.* Thus fissures and veins, being produced by opposite causes—one by tension and the other by pressure—

are formed under opposite conditions. As transverse fissures are produced by the longitudinal stretching of a glacier passing over a *salient* angle, so transverse veins are formed by the longitudinal compression of a glacier passing over a *re-entering* angle. Fig. 58 is a section of the Rhône glacier (Fig. 57), showing the crevasses (*c c c*) produced by the steep declivity, and the veined structure (*s s s*) produced by the compression consequent upon the change of angle on coming out on the plain. The relation of crevasses and vein-structure is still better shown in the ideal section (Fig. 59).

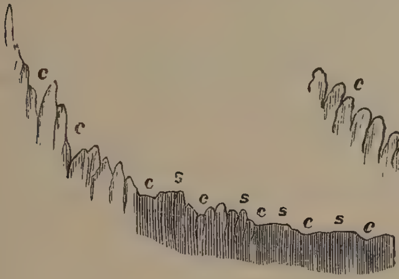

FIG. 58.

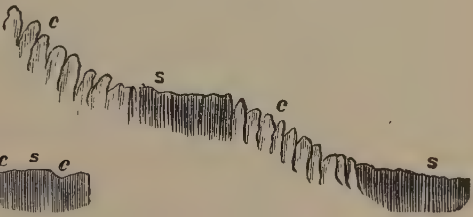

FIG. 59.

Again, as marginal fissures are produced by the pulling of the central portions upon the lagging margins *behind*, so the marginal veins are produced by the crowding or pushing of the swifter central parts on the slower marginal parts *in front* (Fig. 60). The marginal veins are, therefore, inclined to the margin about 45°, but pointing inward and *downward*, and, therefore, at right angles to the crevasses. The relation of these to one another is shown in Fig. 61.

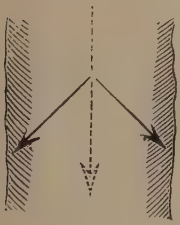

FIG. 60.

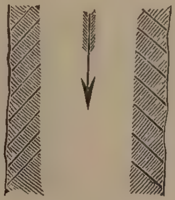

FIG. 61.

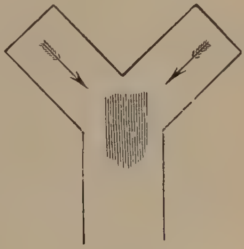

FIG. 62.

Finally, as longitudinal fissures are produced by lateral spreading (Fig. 57), so *longitudinal* veins are produced by lateral compression. This is best seen where two tributaries meet at a high angle (Fig. 62)—for instance, where the Glacier du Géant and the Glacier de Léchaud form the Mer de Glace (Fig. 42). All these facts have been experimentally illustrated by Tyndall.

Physical Theory of Veins.—There is little doubt that veins are formed by pressure at right angles to the direction of the veins; but *how* pressure produces this structure is very imperfectly understood. Probably at least a partial explanation is contained in the following propositions: 1. White vesicular ice by powerful pressure is crushed, the air escapes, and the ice is refrozen into solid blue transparent ice. 2. Ice being a substance which *expands* in freezing, and, therefore, contracts in melting, its freezing and melting point is *lowered by pressure.* Therefore, ice at or near 32° Fahr. is *melted* by pressure. Now, the glacier is under powerful pressure of its own weight, and the stress of this pressure is ever changing from point to point by the changing position of the particles produced by the motion. Thus the glacier in places is ever melting under pressure, and again refreezing by relief of pressure. The melting discharges the air-bubbles, and, in refreezing, the ice is blue. 3. No substance is perfectly homogeneous, and of equal strength in all parts; therefore, this crushing and melting, and consequent conversion of white into blue ice, take place *irregularly* in spots. 4. As ice of a glacier acts like a viscous substance, the final effect of pressure would be to flatten these spots, both white and blue, in the direction of greatest pressure, and *extend* them in a direction at right angles to the pressure, and thus create bands in this direction. 5. Differential motion would also tend to bring the veins into the direction indicated by Forbes.

Floating Ice—Icebergs.

We have already seen (page 50) that at a certain latitude, varying from 46° in South America to about 65° in Norway, glaciers touch the surface of the ocean. Beyond this latitude, they run out to sea often to great distances. By the buoyant power of water, assisted by tides and waves, these projecting floating masses are broken off, and accumulate as immense ice-barriers in polar seas, or are drifted away by currents

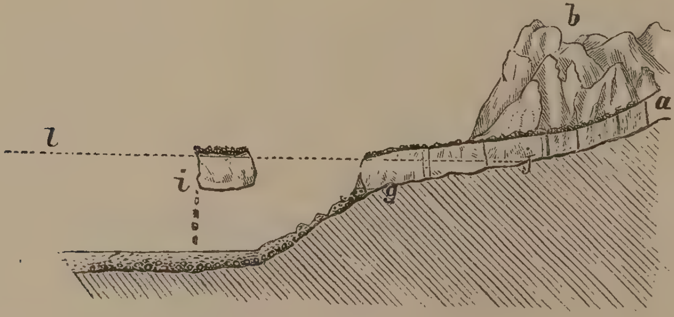

Fig. 63.—Formation of Icebergs.

toward the equator. Such floating fragments of glaciers are called *icebergs.* Fig. 63 is an ideal section, through a glacial valley, in which *a g* is the glacier, *b* the cliffs beyond, *l s'* the sea-level, and *i* an iceberg.

The principal source of the icebergs of the north Atlantic is the coast of Greenland. This country is an elevated table-land, sloping in every direction to a coast deeply indented like Norway, with alternate deep fiords and jutting headlands. The whole table-land is completely covered with an *ice-sheet*, probably several thousand feet thick, moving slowly seaward, and discharging through the fiords as immense glaciers,* which, as already explained, form icebergs. In this remarkable country no water falls from the atmosphere except in the form of snow, and *all the rivers are glaciers.* The geological effects of such a moving ice-sheet may be easily imagined. The whole surface of the country rock must be polished and scored, the general direction of the striæ being *parallel over large areas.*

The antarctic continent is probably similarly, and even more thickly, ice-sheeted, for the humid atmosphere of that region is very favorable to the accumulation of snow and ice. Captain Wilkes found an impenetrable ice-barrier, in many places 150 to 200 feet high, for 1,200 miles along that coast. From this ice-barrier, icebergs separate and are drifted toward the equator.

The formation of icebergs in polar regions, and their drifting into warmer latitudes, to be melted there, are evidently a necessary consequence of the great *law of circulation*, for otherwise ice would accumulate without limit in these regions. But, by glacial motion, the excess is brought down to the sea, broken off as icebergs, carried southward by currents, and there melted and returned into the general circulation of meteoric waters.

General Description.—The *number* of icebergs accumulated about polar coasts is almost inconceivable. Scoresby counted 500 at one view. Kane counted 280 of the first magnitude at one view. They are often 200 and sometimes even 400 feet high, and the mass above water 66,000,000 cubic yards (Dr. Rink). As the specific gravity of ice is 0·918, if these were solid ice, there would be about one twelfth above water; but as glacier-ice is somewhat vesicular, there is about one seventh above water. The *thickness* of some of these icebergs must therefore be 2,000 to 3,000 feet, and their *volume* near 500,000,000 cubic yards, which is about equivalent to a mass one mile square and 500 feet thick. Under the influence of the melting power of the sun unequally affecting different parts, they assume various and often strange forms. The accompanying figure (Fig 64) gives the usual appearance in the northern Atlantic. Those separated from the antarctic barrier present, before they have been much acted upon by the sun, a much more regularly prismatic appearance. Fig. 65 gives the appearance of one of these prismatic blocks or tables, 180 feet high, seen by Sir James Ross in the antarctic seas.

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* Dr. Rink, Archives des Sciences, vol. xxvii, p. 155.

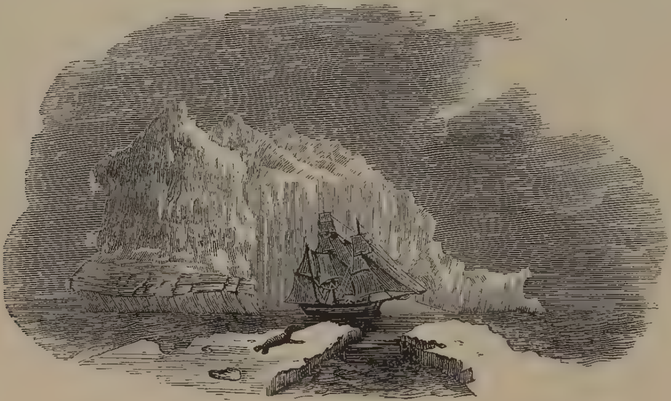

Fig. 64.

Icebergs as a Geological Agent—Erosion.—The polishing and scoring effects of the ice-sheets and of their discharging glaciers must, of course, extend over the sea-bottoms about polar coasts as far as the glaciers touch bottom, which, considering their immense thickness, must be for considerable distances (Fig. 63, *s′* to *g*). This, however, is glacier agency rather than iceberg agency. On being separated they float away, and are carried by currents with their immense loads of earth and bowlders, amounting often to 100,000 tons or more, as far as 40° or even 36° latitude, where, being gradually melted, they drop their burden. If the water be not sufficiently deep, they ground, and being swayed by waves and tides they chafe and score the bottom in a somewhat irregular manner; or, packing together in large fields, and

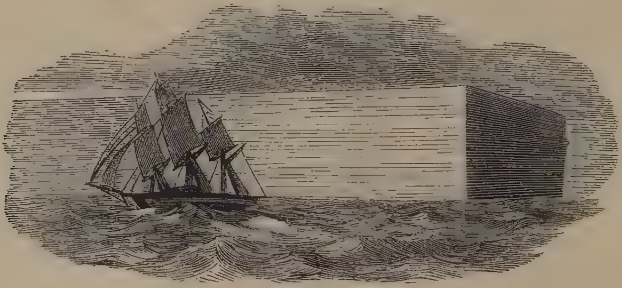

Fig. 65.

urged onward by powerful currents, they may possibly score the bottom over considerable areas somewhat in the manner of glaciers. A large iceberg will ground in water 2,000 and 2,500 feet deep; they have been found by James Ross actually aground in 1,560 feet of water off Victoria Land. A true glaciated surface, however, can not be produced by icebergs.

Deposits.—The bottom of the sea about polar shores is found deeply covered with the materials brought down by glaciers and dropped by icebergs (Fig. 63). Again, similar materials are carried by icebergs as far as these are drifted by currents, and spread on the bottom of the sea everywhere in the course of these currents. Where stranded icebergs accumulate, as on the banks of Newfoundland, large quantities of such materials are deposited. These banks are in fact supposed to have been formed, in part at least, in this way. Such deposits have not been sufficiently examined; they are probably somewhat similar to those of glaciers, exhibiting, however, some signs of the sorting power of water. Balanced stones or bowlders in insecure positions can hardly be left by icebergs.

Shore-Ice.

In cold climates the freezing of the surface of the water forms sheets of ice many inches or even feet thick, and of great extent, about the shores of rivers, bays, and seas. They often inclose stones and bowlders of considerable size, and when loosened in spring from the shore they bear these away, and again drop them at considerable distances from their parent rock. Also such sheets packed together in large masses, and driven ashore by river and tidal currents, and chafed back and forth by waves, produce effects on the shore-rocks somewhat similar to the scoring, polishing, and even the *roches moutonnées* of glacier-action. On a rising or on a subsiding coast such scorings and polishings may extend over wide areas, and thus simulate true glacial action. These effects are well seen on the shores of the St. Lawrence River and Gulf.

The importance of the study of ice-agencies will be seen when we come to explain the phenomena of the Drift or Glacial period.

Comparison of the Different Forms of the Mechanical Agencies of Water.

Rivers and glaciers are constantly cutting down all lands, bearing away the materials thus gathered, and depositing them on the sea-margins. Acting alone, therefore, their effect must be to diminish the height and to extend the limits of the land. Ocean agencies, on the other hand, by tides and currents bear away to the open sea the materials brought down from the land, and thus tend to prevent marginal accumulations; and by waves and tides constantly eat away the coast-line, and thus strive to extend the domain of the sea. Thus, while river and ocean agencies are in conflict with one another at the coast-line, the one striving to extend the limits of the land, and the other of the sea, yet they co-operate with each other in destroying the inequalities of the earth's surface, and are therefore called *leveling agencies.* Moreover, it is evident that the erosion of the land and the filling up of the seas are correlative, and one is an exact measure of the other. Now, we have seen (page 11) that the probable rate at which all continents are being cut down by rivers is about one foot in 4,500 to 5,000 years. But since the ocean is about three times the extent of the land, this spread evenly over the bottom of the sea would make a stratum about four inches thick. Therefore, we conclude that, neglecting the destructive effects of waves and tides on the coast-line, which, according to Phillips,* are small in amount compared with general erosion of the land-surface, we may say that stratified deposits are now forming, or the ocean-bed filling up, at the average rate over the whole bottom of about four inches in 5,000 years.

SECTION 4.—CHEMICAL AGENCIES OF WATER.

Underground Waters and the Origin of Springs.

As we have already seen (page 10), of the rain which falls on any hydrographical basin, a part runs from the surface, producing universal erosion. A second part sinks into the earth, and, after a longer or shorter subterranean course, comes up as springs, and unites with the surface-water to form rivers; while a third portion never comes up at all, but continues by subterranean passages to the sea. This last portion is removed from observation, and our knowledge concerning it is very limited. But there are numerous facts which lead to the conviction that it is often very considerable in amount. In many portions of the sea near shore, springs, and even large rivers, of fresh water, are known to well up. Thus, in the Mediterranean Sea, "a body of fresh water fifty feet in diameter rises with such force as to cause a visible convexity of the sea-surface." † Similar phenomena have been observed in many other places in the same sea, and also in the Gulf of Mexico near the coast of Florida, among the West India Isles, and near the Sandwich Islands. Besides the last mentioned, there is still another portion of subterranean water existing permanently in every part of the earth far beneath the sea-level, filling fissures and saturating sediments to great depths, and only brought to the surface by volcanic forces. This, in contradistinction from the constantly-circulating meteoric water, may be called *volcanic water.*

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* Phillips, Life on the Earth, p. 131.

† Herschel's Physical Geography.

Perpetual Ground-Water.—Passing from the surface downward the ground contains more and more water until it becomes saturated and the water movable. This region of movable water rises and falls with the season, but never below a certain level depending upon the climate.

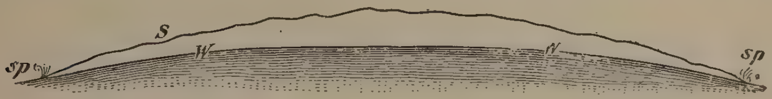

Fig. 66.—Diagram of Perpetual Ground-Water: *s s*, surface of ground; *w w*, ground-water; *sp sp*, hill-side springs.

The upper limit of always movable water is called the level of "perpetual ground-water." It is deepest on the hill-tops and comes nearer the surface toward the valleys, where under favorable conditions it may issue on the surface as springs, as in Fig. 66.

Springs.—The appearance of subterranean waters upon the surface constitutes *springs.* They occur in two principal positions, viz.: 1. Upon *hill-sides*, just where porous, water-bearing strata such as *sand* outcrop, underlaid by impervious strata like *clay ;* 2. On *fissures* penetrating the country rock to great depth.

Most of the *small springs* occurring everywhere belong to the first class. The figure (Fig. 67) represents a section of a hill composed mostly of porous strata, *b*, but underlaid by impervious clay stratum, *c*. Water falling upon the surface sinks through *b* until it comes in contact with *c*, and then by hydrostatic pressure moves laterally until it emerges at *a*. Sometimes this is a geological agent of considerable importance, modifying even the forms of mountains, and producing land-slips, etc. Thus the Lookout and Raccoon Mountains, in Tennessee, are table-mountains of nearly horizontal strata, separated by erosion-valleys. These mountains are all of them capped by a sandstone stratum about 100 feet thick, underlaid by shale. The water which falls upon the mountain emerges in numerous springs all around where the sandstone cap comes in contact with the underlying shale. The sandstone is

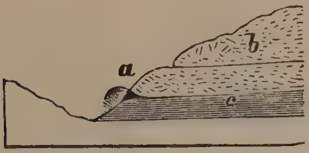

Fig. 67.—Hill-side Spring.

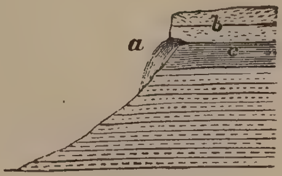

Fig. 68.

gradually undermined, and falls from time to time, and thus the cliff remains always perpendicular (Fig. 68).

Large springs generally issue from fissures. Water passing along the porus stratum *b*, perhaps from great distance, and prevented from rising by the *overlying* impervious stratum *c*; coming in contact with a fissure, immediately rises through it to the surface at *a* (Fig. 69).

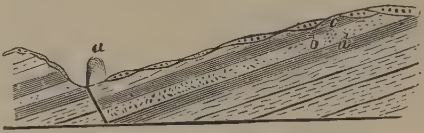

FIG. 69.—Fissure-Spring.

Artesian Wells.—If subterranean streams have their origin in an elevated region, *a d*, composed of regular strata dipping under a lower flat country, *c*, then the subterranean waters passing along any porous stratum as *a* (Fig. 70), and confined by two impermeable strata, *b* and *d*, will be under powerful hydrostatic pressure, and will, therefore, rise to the surface, perhaps with considerable force, if the stream be tapped by boring at *c*. Borings by which water is obtained in this manner are called Artesian wells, from the French province Artois, where they were first successfully attempted. The source of the water may be 100 miles or more distant from the well. Some of these wells are very deep. The Grenelle Artesian in Paris is 2,000 feet deep. At the moment of tapping the stream, a powerful jet was thrown 112 feet high. One in Westphalia, Germany, is 2,385 feet deep; one at St. Louis, 3,843 feet; one at Louisville, Kentucky, 2,852; one near Berlin, 4,172 feet; one near Pittsburg, Pa., 4,625; and one near Leipsic, 5,735 feet.* In parts of Alabama and California the principal supply of water for agricultural purposes is drawn from these wells.

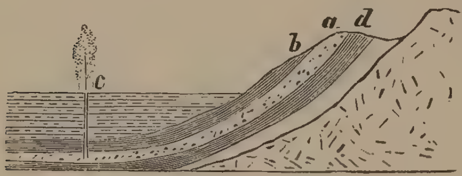

FIG. 70.—Artesian Well.

Thus there is on all coasts a constant flowing of water, both superficial and subterranean, into the sea. Their relative amount it is impossible to determine. Much depends upon the configuration of the country and the nature of the strata. The heavy hydrostatic pressure to which subterranean water is subjected, especially in elevated countries, brings the larger portion of it to the surface as springs. But, in limestone regions (this rock being affected with frequent and large fissures, and open subterranean passages, as will be hereafter explained), large subterranean rivers often exist, and these even after coming to the surface are often re-engulfed, and finally reach the sea by subterranean passages. The same is true also of regions covered with recent lava-flows; for these also are full of caves and galleries (page 94). The largest springs, therefore, generally occur either in limestone or in volcanic countries. From the Silver Spring, in Florida, issues a stream navigable for small steamers up to the very spring itself. The country for sixty miles around is entirely destitute of superficial streams, the whole drainage being subterranean, and coming up in this spring.* About Mount Shasta all the streams head in great springs.

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* Science, xiv, 250, 1889.

Chemical Effects of Subterranean Waters.—We have already seen (page 6) how atmospheric water disintegrates rocks, dissolving out their soluble parts, and reducing their unsoluble parts to soils. Springs, therefore, always contain the soluble matters. In granite regions they contain potash; in limestone regions they contain lime, and are called *hard;* in other cases they contain salt, and are *brackish;* when the saline ingredients are unusual in quantity or in kind, they are called *mineral* waters.

Limestone Caves.—In most rocks, the insoluble part left as soil is far the largest, only a small percentage being dissolved. In such rocks, therefore, the resulting soil fills the whole space originally occupied by the rock. But in the case of limestone the whole rock is soluble. Therefore, in limestone regions, percolating waters dissolve the limestone, hollow out *open passages*, and form immense *caves.* Water charged with limestone, dripping from the roofs and falling on the floors of these caves, deposit their limestone by evaporation, and form *stalactites* (Fig. 71), *a a*, and *stalagmites*, *b b*, which, meeting each other, form *limestone pillars*, *c c.* The great Mammoth Cave, in Kentucky; Wier's Cave, in Virginia, and Nicojack Cave, in Tennessee, are familiar examples. As might be expected, subterranean rivers are often found in these caves. This is the case in the Mammoth Cave and in Nicojack Cave.

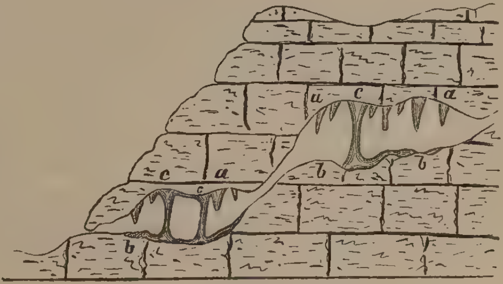

Fig. 71.—Limestone Cave.

Thus, as the same river will erode or deposit according as it is under-loaded or overloaded with sediment; so the same underground stream may hollow out passages by solution or fill them up by deposit according as its waters are under-saturated or over-saturated with mineral matter.

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* The exceptional transparency of limestone waters is due to the property, possessed by lime in a remarkable degree, of flocculating and precipitating clay sediments.

There are many other effects of subterranean waters of the greatest importance, such as the formation of fossils, the filling of mineral veins, the metamorphism of rocks, etc.; but these will be taken up each in its appropriate place.

Chemical Deposits in Springs.

Deposits of Carbonate of Lime.—We have just seen that ordinary subterranean waters in limestone districts, and, therefore, containing small quantities of carbonate of lime, deposit this substance *only very slowly by drying*, as stalactites and stalagmites; but in *carbonated springs* in limestone districts a very rapid deposit of lime carbonate often occurs.

Explanation.—In order to understand this, it is necessary to remember: 1. That lime carbonate is insoluble in pure water, but soluble in water containing carbonic acid; 2. That the amount of carbonate dissolved is, up to a limit, proportionate to the amount of carbonic acid contained; 3. That the amount of carbonic acid which may be taken in solution by water is proportionate to the pressure.

Now, there are two sources of carbonic acid, viz., atmospheric and subterranean. All water contains carbonic acid from the atmosphere, and will, therefore, dissolve limestone, but this deposits only slowly by drying, as already explained. But in many districts, especially in volcanic districts, there are abundant subterranean sources of carbonic acid. If subterranean waters come in contact with such carbonic acid, being under heavy pressure, they will take up a large quantity of this gas; and if such water comes to the surface, the pressure being removed, the gas will escape in bubbles. This is a *carbonated spring.* If, further, the subterranean waters, thus highly charged with carbonic acid, come in contact with limestone rocks, or rocks of any kind containing lime carbonate, they will dissolve a proportionately large amount of this carbonate; and when they come to the surface, the escape of the carbonic acid causes the lime carbonate to deposit abundantly. Thus around *carbonated* springs in *limestone* districts, and along the course of the streams which issue from them, are generally found extensive deposits of this substance. Being found mostly in volcanic regions, these springs are commonly hot.

Kinds of Materials.—The material thus deposited is usually called travertine, but is very diverse in appearance. If the deposit is quiet, the material is *dense;* if tumultuous, the material is *spongy;* if no iron is present, it is *white* like marble; but if iron be present, its oxidation colors it yellow, brown, or reddish, If the amount of iron be variable, the stone is beautifully *striped.* If objects of any kind, branches, twigs, leaves, are immersed in such waters, they are speedily incrusted, often in the most beautiful manner.

Examples of such deposits are found in all countries. At the baths of San Vignone, Italy, a carbonated spring issuing from the top of a hill has covered the hill with a stratum of white, compact travertine 250 feet thick. In the conduit-pipe which leads the water to the baths, the deposit accumulates six inches thick every year. A similar deposit of travertine occurs at the baths of San Filippo. At this latter place, beautiful *fac-similes* of medallions, coins, etc., are formed by placing these objects of art in the spray of an artificial cascade. In Virginia, around the "Old Sweet" and the "Red Sweet" Springs, and in the course of the stream which flows from them for several miles, a brownish-yellow deposit of travertine has accumulated to the depth of at least thirty feet. The spray of Beaver Dam Falls, about three miles below the springs, incrusts every object in its reach with this deposit.

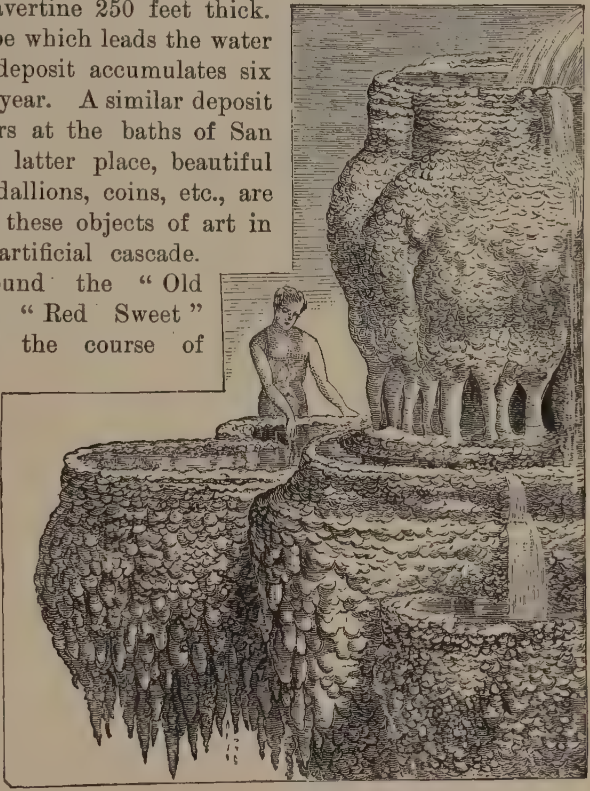

FIG. 72.—Deposits from Carbonated Springs.

In California, all about the shores of Lake Mono, abundance of beautiful and strangely-branched coralline forms are found, which have evidently been formed in a somewhat similar way. In the region of the Yellowstone Park, deposits of travertine from waters of hot springs running down a steep incline, in a succession of cascades, assume the most beautiful forms, as shown in the accompanying figure (Fig. 72), taken from Hayden.

Deposits of Iron.—Iron carbonate, like lime carbonate, is to some extent soluble in water containing carbonic acid. Subterranean waters, therefore, which always contain atmospheric carbonic acid, when they meet this carbonate, will take up a small quantity in solution. Such waters are called *chalybeate*. On coming to the surface the iron gives up its carbonic acid, is peroxidized, becomes insoluble, and is deposited. As the presence of organic matter is usually necessary to bring the iron into a soluble condition, the full discussion of this very interesting subject is reserved until we take up organic agencies.

Deposits of Silica.—Silica is soluble in alkaline waters, especially if the waters be *hot*. Such waters, reaching the surface and cooling, deposit the silica in great abundance, often at first in a gelatinous condition, but drying to a white porous material called *siliceous sinter*. Examples of such deposits are found in all geysers, as in those of Iceland, and in the Steamboat Springs in Nevada, and especially in the wonderful geysers of Yellowstone Park. Such deposits are confined to volcanic regions, the volcanic rocks furnishing both the alkali and the heat. We will discuss these again under Igneous Agencies.

Deposits of Sulphur and Gypsum.—Springs containing sulphide of hydrogen (H_2S), usually called *sulphur-springs*, sometimes deposit sulphur by oxidation of the hydrogen ($H_2S+O=H_2O+S$), and sometimes gypsum. This latter deposit is caused by the more complete oxidation of the sulphide of hydrogen, forming sulphuric acid ($H_2S+4O=H_2SO_4$), and the reaction of this acid on lime carbonate held in solution in the same water.

Chemical Deposits in Lakes.

Salt Lakes and Alkaline Lakes.—Salt lakes may be formed either —1. By the *isolation of a portion of sea-water* in the elevation of sea-bottom into land; or, 2. By *indefinite concentration of river-water* in a lake without an outlet. Thus, the Dead Sea, Lake Elton, and the brine-pools of the Russian steppes, are usually supposed to be concentrated remains of isolated portions of the sea,[*] for their waters are highly concentrated mother-liquors of sea-water, having a composition very similar to the mother-liquors of the *salt-maker*.[†] The Caspian Sea, on the other hand, although elevated lake-margins show that much of its waters has dried away, is still much fresher than sea-water. This fact, together with the composition of its waters, is usually supposed to indicate that it has been formed by the simple concentration of the waters of a once fresh lake.[‡] Yet there are some evidences, as we shall see hereafter (p. 596), of this sea having been once connected with the Black Sea and with the Arctic Ocean. It is probable that the Caspian was first isolated from the ocean as a salt lake, then freshened by an outlet, and finally re-concentrated to its present conditions. The composition of the waters of the Great Salt Lake of Utah would seem to indicate its origin in the isolation of sea-water; but there are evidences of its once having had an outlet; in which case it must have been fresh.*

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[*] Bischof, Chemical and Physical Geology, vol. i, p. 396.

[†] And yet the presence of fresh water shells on the elevated old margins of the Dead Sea seem to indicate that it may have been a fresh lake emptying through the Arabah valley into the Gulf of Akabah (Rice).

[‡] Bischof, Chemical and Physical Geology, vol. i, p. 91.

Alkaline lakes can only be formed by the second way. Both salt and alkaline lakes, therefore, may be formed by indefinite concentration of river-water in a lake without outlet. Whether the one or the other is formed depends on the composition of the river-water. If alkaline chlorides predominate, a salt lake will be formed; but if alkaline carbonates, an alkaline lake. Such alkaline lakes are found in Hungary, in Lower Egypt, and in Persia. In our own country, Lake Mono, fifteen miles long, and twelve miles wide, and Lake Owen, of at least equal dimensions, are examples of alkaline lakes. The waters of Lake Mono consist principally of a strong solution of *carbonate of soda* and chloride of sodium, with a little carbonate of lime and borate of soda.† Borax lakes, which are found in California and a few other countries, can be formed only by the concentration of the water of springs of exceptional composition.

Conditions of Salt-Lake Formation.—Spring and river waters always contain a small quantity of saline matter derived from the rocks and soils. Suppose, then, we have a lake supplied by rivers: 1. If the supply of water by rivers is greater than the loss by evaporation from the lake-surface, then the water will rise until, finding an outlet in the rim of the lake-basin, it flows into the sea. In this case the lake will remain *fresh*, or the quantity of saline matter will be inappreciable. But if, on the other hand, the loss by evaporation is greater than the supply by rivers, the lake will decrease in extent, and therefore in evaporating surface, until an equilibrium is established. Now all the saline matters constantly leached from the earth accumulate in the lake without limit; the lake, therefore, must eventually become saturated with saline matter, and afterward begin to deposit salt. It is evident, then, that whether a lake is fresh or salt depends upon whether or not it has an outlet, and this latter depends upon the relation of supply by rivers to loss by evaporation. Lakes are mostly fresh, because much more water falls on continents than evaporates from the same surface, the excess running back to the sea by rivers. It is only in certain parts of the continents, where the climate is very dry, that there is no such excess. In these regions alone, therefore, can salt lakes exist. Such regions occur in the interior of Asia, on the plateau of Mexico, in the basin of Utah, and in several other places.

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* Gilbert, Wheeler Report for 1872, p. 49.

† The probability of Great Salt Lake having been produced by simple evaporation of river-water is increased by the difference in the composition of the waters of lakes in this general region. Where sedimentary rocks prevail, as in Utah, they are salt; where volcanic rocks prevail, as about Mono and Owen, they are alkaline.

Even in case a salt lake is originally formed by the isolation of a portion of sea-water, whether it remains a salt lake or gradually becomes fresh will depend upon the conditions we have already mentioned. For example: if the Mediterranean should be separated from the Atlantic at the straits of Gibraltar, it would not only remain a salt lake, but would diminish in area, and finally deposit salt. This we conclude, because the water of the Mediterranean seems to be a little more salt than that of the Atlantic. If, on the contrary, the Black Sea were separated from the Mediterranean, or the Baltic from the Atlantic, or the bay of San Francisco from the Pacific, the supply by rivers, in the case of these inland seas being greater than their loss by evaporation, they would rise until they found an outlet, and then would be gradually rinsed out, and become fresh. Lake Champlain was, in very recent geological time, an arm of the sea. When first isolated it was salt. It has become fresh by this process.

Saltness of the Ocean.—It is obvious that only the *last* reservoir is salt. Thus Lake Tahoe runs into Pyramid Lake, but only the latter is salt; Lake Utah, a fresh lake, runs into Great Salt Lake; the Sea of Galilee, a fresh lake, empties into the Dead Sea, a salt lake. Now, the ocean is, of course, the *last reservoir* of circulating waters. Is its saltness to be similarly accounted for? Not exactly; salt lakes receive their salt largely from strata deposited in the ocean and salted thereby, but the ocean preceded all stratified rocks. Nevertheless the ocean, too, received its salt from the rocks. Throughout the whole geological history of the earth there has been a progressive differentiation of the soluble and the insoluble parts of the rocks, the one accumulating in the ocean, the other remaining in the rocks and soils.

Deposits in Salt Lakes.—The nature of the chemical deposits in salt lakes will depend upon the manner in which these lakes have been formed. We will take the simplest case, viz., that of a lake formed by the isolation of sea-water, and its concentration by evaporation. In this case the substance first deposited would be *gypsum;* for this substance is insoluble in a saturated brine, and therefore always deposits first in the artificial evaporation of sea-water in salt-making. Upon the gypsum would be deposited *salt.* Meanwhile, however, the rivers during their flood-season would bring down *sediments.* During the flood-season, the supply of water being greater than loss by evaporation, the deposit of salt or gypsum would cease; while during the dry season the deposit of sediment would cease, and the evaporation being now in excess, the deposit of salt would recommence. Thus the deposits in the bottom of salt lakes probably consist of alternations of salt and sediment, the whole underlaid by layers of gypsum. These views have been confirmed by observation. During the dry season Lake Elton deposits annually a considerable layer of salt. Wells dug near the margin of this lake revealed a hundred alternations of salt and mud, the salt-beds being many of them eight or nine inches thick.* Most of the salt has already deposited; for the water of this lake is an almost pure *bittern.* The great predominance of chloride of magnesium in Dead Sea water shows that it is a mother-liquor, from which immense quantities of common salt have already been deposited. Similar alternations, therefore, no doubt exist in the bottom of this sea.† The *Great Salt Lake*, in Utah, is also a saturated brine depositing salt, as is proved by the incrustations of salt about its margin in dry seasons; but the deposit has not progressed so far in this case as in the preceding. The great extent to which the waters of this lake have dried away and become concentrated is further shown by *old lake-margins* far beyond the limits, and several hundred feet above the level, of the present shoreline. Similar phenomena are observed about other salt lakes, especially about the Caspian Sea (Murchison).

In the case of salt lakes, either formed entirely, or modified, by river-water, the deposits are probably much more complex and various —sometimes salt, sometimes carbonate of lime, and sometimes sulphate of lime. Immense deposits, mostly of carbonate of lime, are found about the salt lakes of Nevada. They form a conspicuous feature of the scenery about Pyramid Lake.

Deposits are also sometimes formed in lakes which are not salt. For example: the Solfatara Lake, Italy, is formed by the accumulation of the water from warm carbonated springs, similar to those of San Filippo and San Vignone. In this lake, therefore, deposits of travertine are forming. Although these deposits take place in a lake, they properly belong to deposits from springs, since they do not take place entirely by concentration, but partly also by escape of carbonic acid.

Chemical Deposits in Seas.

Concerning these little is known. It is certain, however, that all rivers carry to the sea carbonate of lime in solution, and some of them in considerable quantities. There is scarcely any river-water which contains less carbonate of lime than sea-water; many rivers contain four times as much.‡ This carbonate of lime thus constantly carried into the sea must eventually deposit in some form. Usually, however, sea-water is kept below the saturating point for this substance, by its constant withdrawal by shells and corals, as will be explained under

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* Bischof, Chemical and Physical Geology, vol. i, p. 405.

† Ibid., p. 400.

‡ Ibid., p. 179.

Organic Agency. But in shallow bays nearly cut off from the sea, or in salt lagoons on the sea-margin near the mouths of rivers in dry climates, and subject to occasional overflows by the sea and floodings by rivers, carbonate of lime and sulphate of lime may deposit by evaporation. At the mouths of many rivers, whose waters contain much carbonate of lime, as, for instance, the Rhine, the delta deposit is cemented into hard rock by means of this substance. On shores of coral seas, as upon the Keys of Florida, the coast of the West India Islands, and the islands of the Pacific, shore-material is consolidated into hard rock by the same means. On many shores in tropical regions the waves, being driven up on flat beaches far inland, leave sea-water inclosed in shallow pools, which by evaporation give rise to calcareous deposits which are increased by the frequent alternate influx and evaporation of sea-water. Conglomerate rocks are thus forming at the present time in the Canaries and many other places.

CHAPTER III.

IGNEOUS AGENCIES.

THE agencies thus far considered tend to reduce the inequalities of the earth by cutting down the continents and filling up the seas. Their final effect, if unopposed, would be to bring the whole surface to one level, and thus to make the empire of the sea universal. This is prevented by igneous agencies, which tend, by elevation of land and depression of sea-bottoms, to increase the inequalities of the earth-surface, and thus to *increase the area and the height of the land.* These two opposing agencies have entirely different sources. The one is external, or *sun*-derived; the other internal, or *earth*-derived. The one gives the great outlines of earth-features; the other sculptures these into forms of beauty. The one rough hews; the other shapes. The actual forms of earth at any time is the result of the state of balance between them. All the different forms of igneous agency are connected with the interior heat of the earth. This must, therefore, be first considered.

SECTION 1.—INTERIOR HEAT OF THE EARTH.

Stratum of Invariable Temperature.—The mean surface temperature of the earth varies from 80° at the equator to nearly 0° at the poles. The rate of decrease in passing from the equator to the poles is not the same in all longitudes; the isotherms, or lines joining places of equal mean temperatures, are therefore not parallel to the lines of latitude, but quite irregular. The mean temperature of the whole earth-surface is about 58°. There is also in every locality a *daily* and an *annual variation* of temperature. As we pass below the surface both the daily and annual variations become less, until they cease altogether. The *stratum of no daily variation* is but a foot or two beneath the surface; but the stratum of no *annual* variation, or *stratum of invariable temperature* in temperate climates, is about sixty to seventy feet deep. The temperature of the invariable stratum is nearly the mean temperature of the place. The *depth* of the invariable stratum depends upon the amount of annual variation; it is, therefore, least at the equator, and increases toward the poles. At the equator it is only one or two feet beneath the surface;* in middle latitudes about sixty feet, and in high latitudes probably more than a hundred feet.† It is, therefore, a spheroid more oblate than the earth itself. The temperature of the earth everywhere within this spheroid is unaffected by external changes.

Increasing Temperature of the Interior of the Earth.—Beneath the invariable stratum the temperature of the earth everywhere increases, for all depths to which it has been penetrated, at an average rate of about 1° for every 53 feet. This very important fact has been determined by numerous observations on the temperature of mines and

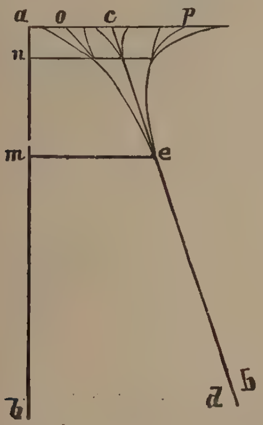

FIG. 73.

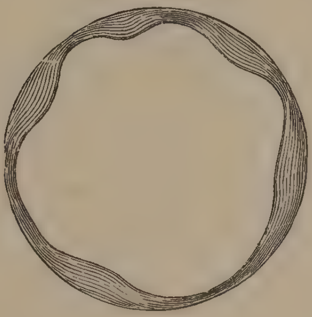

FIG. 74.

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* Humboldt, Cosmos, Sabine's edition, vol. i, p. 165.

† In polar regions, or the region of *perpetual ground-ice*, the stratum of invariable temperature probably again rises nearer the surface, on account of the property of ice of retaining its temperature by melting.

of Artesian wells in almost every part of the earth. All the facts thus far stated are graphically illustrated in the accompanying figure (Fig. 73), in which the line *a b* represents depth below the surface, and the diverging line *c d* the increasing heat; *m* the invariable stratum; *n* the line of no daily variation; the curves *p e*, *c e*, *o e*, the temperatures in summer, autumn, and winter, respectively; the space *c e o* the annual swing of temperature; and the smaller curves meeting on the the line *n*, the daily variation or swing of temperature.

We have given the rate of increase as about 1° in 53 feet. It varies, however, in different places, from 1° in 30 feet to 1° in 90 feet. Except in the vicinity of volcanic action, this difference is probably due to varying *conductivity* of the rocks. The lines, or rather surfaces, which join places in the interior of the earth, having equal temperatures, may be called *isogeotherms.* If the rate of increase were everywhere the same, the isogeotherms would be regularly concentric; but, as this is not the case, they are irregular surfaces (Fig. 74), rising nearer the earth-surface and closing upon one another where the conductivity is poor, and sinking deeper and separating where the conductivity is greater.

Constitution of the Earth's Interior.—From the facts given above it is probable that the temperature of the interior of the earth is very great. A rate of increase of 1° for every 53 feet would give us, at the depth of twenty-five or thirty miles, a temperature sufficient to fuse most rocks. Hence it has been confidently concluded by many that the earth, beneath a comparatively thin crust of thirty miles, must be liquid. A crust of thirty miles on our globe is equivalent to a crust of less than one tenth of an inch in a globe two feet in diameter. There are, however, many objections to this conclusion. The question of the interior constitution of the earth is one of extreme difficulty and complexity, and science is not yet in a position to solve it completely. Nevertheless, it can be proved that the solid crust must be much thicker than is usually supposed, if, indeed, there be any general interior fluid at all.

The argument for the interior fluidity of the earth, beneath a crust of only thirty miles, proceeds upon two suppositions, viz.: 1. That the *interior temperature increases at the same rate for all depths;* and, 2. That the *fusing-point* of rocks is *the same for all depths.* Now, neither of these can be true.

1. **Rate of Increase not Uniform.**—Although we have spoken of 1° for *every* 30 feet or 50 feet or 90 feet, yet it must not be supposed that observation gives a uniform rate of increase at any place. On the contrary, the rate is sometimes faster and sometimes slower, depending on the conductivity of the rock penetrated, and on other causes little understood. The rate given is always an *average.* In other words,

observation gives the *fact* of increase, but not the *law*. We are thus thrown back on general reasoning.

If two bars, one a good conductor, like metal, and the other a bad conductor, like charcoal, be heated red hot at one end, and the rate of decreasing temperature—fall of heat—toward the other be observed, it will be found that the rate is very rapid in the case of the charcoal, so that a temperature of 60° is reached at the distance of two or three inches; while in the case of the metal the rate of decrease is much slower, and 60° is only reached at a distance of several feet. Conversely, the rate of *increase*, or *rise*, in passing toward a source of heat, is rapid in the case of the bad conductor, and slow in the case of the good conductor. Now, the average density of materials at the surface of the earth is about 2·5, but the average density of the whole earth is more than 5·5; therefore the density of the central portions must be much more than 5·5. It has been estimated at 16·27.[*] There can be no doubt, therefore, that the density of the earth increases toward the center; and as this increase is probably largely the result of pressure, it is probably somewhat regular. Whatever be the cause the effect would be to *increase the conductivity for heat*, and therefore to *diminish* the rate of increasing temperature. Thus it follows that, though in a homogeneous globe the melting-point of rocks (3,000°) would be reached at the depth of thirty miles, yet, in a globe increasing in density toward the center, we must seek this temperature at a greater depth.

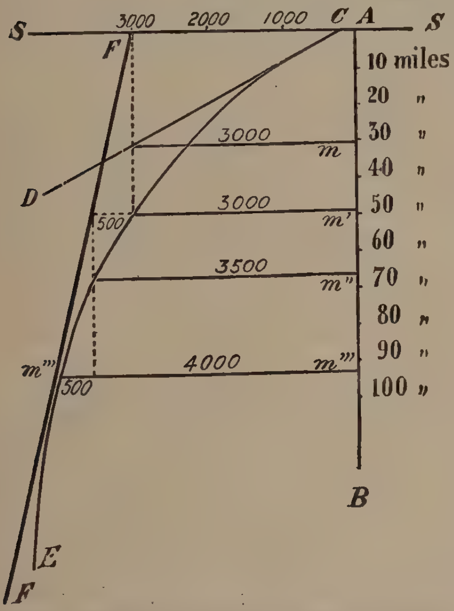

FIG. 75.—Diagram illustrating the Increase of Temperature and of Differing Power with Increasing Depth.

If *A B* (Fig. 75), representing *depth* from the surface *S S*, be taken as absciss, and *heat* be represented by ordinates, then, in a homogeneous earth, *C D* would represent uniform increase of heat, and the heat ordinate of 3,000°, *m*, would be reached at the depth of *A m* = thirty miles. But in an earth increasing in density, and, therefore, in conductivity, the rate would not be uniform, but gradually decreasing. This would be represented, not by a straight line, *C D*, but by a curved line, *C E*; and the ordinate of 3,000° would not be reached at thirty miles, but at a much greater depth—say at *m′*, of fifty miles.*

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[*] Cosmos, vol. iv, p. 33.

2. **Fusing-Point not the same for all Depths.**—Nearly all substances expand in the act of melting, and contract in the act of solidifying. Only in a few substances, like ice, is the reverse true. Now, the fusing-point of all substances which expand in the act of fusing must be *raised by pressure*, since the expanding force of heat, in this case, must overcome not only the cohesion, but also the pressure. That this is true, has been proved experimentally for many substances by Hopkins. † But granite and other rocks have been proved to expand in fusing; therefore the fusing-point of rocks is raised by pressure, and must be greatly raised by the inconceivable pressure to which they are subjected in the interior of the earth. For this reason, therefore, we must again go deeper to find the interior *fluid*. In the figure, *m′* is the point where we last found the fusing-point of 3,000°. But this is the fusing-point on the surface, or under atmospheric pressure. The pressure of fifty miles of rock would certainly greatly raise the fusing-point. Let the line *F F* represent the temperature of fusing-point with increasing depth. Suppose it is thus raised to 3,500°: to find this we must go still deeper, to *m″*, perhaps seventy miles in depth. But the increased pressure would again raise the fusing-point; and thus, in this chase of the increasing heat after the flying fusing-point, *where* the former would overtake the latter, or whether it would overtake it at all, science is yet unable to answer.

From this line of reasoning, therefore, we conclude that the solid crust of the earth *must* be much thicker than is usually supposed, and there *may* be even no interior liquid at all.

Astronomical Reasons.—There is another and entirely different line of reasoning which has led some of the best mathematicians and physicists to the same result. According to the *thin-crust theory*, the earth is still *substantially a liquid globe*, and therefore under the attractive influence of the sun and moon it ought to behave like a yielding liquid. Now, according to Hopkins, Thomson, and others, the earth in all its astronomical relations behaves like a rigid solid—a solid *more rigid than a solid globe of glass*—and the difference between the behavior of a liquid globe and a solid globe could easily be detected by astronomical phenomena.* A complete exposition of the proof would be unsuitable to an elementary work. Suffice it here to say that the force of these arguments has led some geologists to the conclusion that the earth must be regarded as a substantially solid and very rigid globe; that volcanoes are openings into *local* reservoirs of liquid, not into a *general* liquid interior—into subterranean *fire-lakes*, not into an interior *fire-sea;* and that, therefore, the theories of igneous phenomena must be constructed on the basis of a substantially *solid*, not a substantially *liquid*, earth.

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* Even in a homogeneous earth—if cooled from a former incandescent condition—the rate of increasing heat, as shown by Kelvin, would be represented by a curved line, as in the figure.

† American Journal of Science and Art, ser. II, vol. xxxii, p. 367.

There are many phenomena, however, especially the great lava-floods to be described hereafter and the instability of the crust-level under increase and decrease of weight by sedimentation and erosion, which seem to require an unlimited supply of liquid matter at no great distance beneath the surface. Many geologists, therefore, find a compromise in the view that there exists *a liquid or semi-liquid layer*, either universal or over large areas, *between the solid crust and a solid nucleus.* This is called the *sub-crust layer.* This seems, on the whole, the most probable view.† We have called it a liquid or semi-liquid layer. Such it would be, if the line of increasing temperature $C\ E$ touched the line of fusing-point $F\ F$ at m'''. But it may be only a layer of nearest approach to fusion, as represented in Fig. 75, and therefore a layer of greatest instability, i. e., liable to fusion by *relief of pressure.* This seems the most probable condition. Taken as a whole, however, the earth must be regarded as substantially solid.

The interior heat of the earth manifests itself at the surface in three principal forms, viz., *volcanoes*, *earthquakes*, and *gradual oscillations of the earth's crust.*

SECTION 2.—VOLCANOES.

Definition.—A volcano is usually a conical mountain, with a funnel-shaped, or pit-shaped, or cup-shaped opening at the top, through which are ejected materials of various kinds, always hot, and often in a fused condition. The activity of volcanoes is sometimes *constant*, as in the case of Stromboli, in Italy, and Kilauea, in Hawaii, but more commonly *intermittent*, i. e., having periods of eruption alternating with periods of more or less complete repose. Volcanoes which have not been known to erupt during historic times are said to be *extinct.* It is impossible, however, to draw the line of distinction between active and extinct volcanoes. Vesuvius, until the great eruption which overthrew the ancient cities of Herculaneum and Pompeii, was regarded as an extinct volcano. Since that time it has been very active. Krakatoa, after a silence of 200 years, burst out in 1883 in the greatest eruption known.

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* Thomson has recently reaffirmed these conclusions with still greater positiveness.—Nature, vol. xiv, p. 426; American Journal of Science and Art, vol. xii, p. 336, 1876.

† American Geologist, vol. i, p. 382, vol. ii, p. 28, and vol. iv, p. 38.

Size, Number and Distribution.—Some volcanoes are among the loftiest mountains on our globe. *Aconcagua*, in Chili, is 23,000 feet, *Cotopaxi*, in Peru, 19,660 feet in height. These volcanic cones, however, are situated on a high plateau; their height, therefore, is not due to volcanic eruptions entirely. But *Mauna Loa*, in Hawaii, nearly 14,000 feet, and Mount Etna, 11,000 feet high, seem to be due entirely, and Mount Shasta, California, 14,440 feet, Rainier, State of Washington, 14,444, almost entirely to this cause. The crater of Mauna Loa is two and a half miles across; that of Kilauea three miles across and 1,000 feet deep.

The *number* of known volcanoes, according to Humboldt, is 407, and of these 300 to 350 are known to have been active in the last 160 years. The actual number is, however, probably much greater. It has been estimated that, in the archipelago about Borneo alone, there are 900 volcanoes.* The *distribution* of volcanoes is remarkable. (*a*) They are almost entirely confined to the *vicinity of the sea.* Two thirds of them are found on islands in the midst of the sea, and the remainder, with the exception of a few in the interior of Asia, are near the sea-coast. Those on the islands in the sea, probably commenced, most of them, at the *bottom of the sea*, the islands having been formed by their agency. New islands have been suddenly formed under the eye of observers in the Mediterranean and in the Pacific Ocean. The basin of the Pacific is the great theatre of volcanic activity, nearly seven eighths of all known volcanoes being situated on its coasts or on islands in its midst. (*b*) Volcanoes are, moreover, distributed in groups (as the Hawaiian volcanoes, the Mediterranean volcanoes, the Icelandic volcanoes, the West Indian volcanoes, the volcanoes of Auvergne, etc.), or along extensive lines as if connected with a great *fissure* of the earth's crust. The most remarkable linear series of volcanoes is that which belts the Pacific coast. Commencing with the Fuegian volcanoes it runs along the whole extent of the Andes, then along the Cordilleras of Mexico, the Rocky Mountains, then along the Aleutian chain of islands, Kamtchatka, the Kurile Islands, Japan Islands, Philippines, New Guinea, New Zealand, to the antarctic volcanoes Mounts Erebus and Terror, thence back by Deception Island to Fuegia again, thus completely encircling the globe. (*c*) Volcanoes are generally formed in comparatively *recent strata.* This seems to be connected with their relation to the sea; for recent strata are abundant about the sea-coast, and the most recent are now forming in the bed of the sea. The extinct volcanoes of France and Germany are in *tertiary* regions. Possibly the retiring of the sea has extinguished them. In the oldest strata volcanic activity has apparently died out long ago.

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* Herschel, Physical Geology, p. 113.

Phenomena of an Eruption.—The phenomena of an eruption are very diverse. Sometimes there is a gradual melting of the floor of the crater, and then a rising and boiling of the liquid contents until they *quietly* overflow and form immense streams of lava extending fifty to sixty miles. After the eruption, the melted lava again sinks and cools, and solidifies, to form the floor of the crater until another eruption. This is the case with the Hawaiian and many other volcanoes in the South Seas. In other cases, as in the Mediterranean volcanoes, and especially in many in the Indian Ocean, the eruption is fearfully *explosive.* In such cases the eruption is usually preceded by premonitory earthquakes and sounds of subterranean explosions; then the bottom of the crater is blown out with a violent explosion, throwing huge rocky fragments to great distances, often many miles; then the melted lava rises and overflows in streams running down the side of the mountain. The rise and overflow of lava are accompanied with violent explosions of gas which throw up immense quantities of ashes and cinders 6,000 and even 10,000 feet above the crater.* The fine ashes from Krakatoa are said to have been carried, by the uprush of gas and vapors, to the amazing height of 17 miles.† In the great eruption of Tomboro, in the island of Sumbawa near Java, in 1815, these explosions were heard in Sumatra, 970 miles distant.‡ Explosions of Krakatoa were heard 2,000 and even 3,000 miles.# The emission of gas usually continues after all other ejections cease. Violent storms and heavy rain accompany the eruption, and when the mountain reaches into the region of perpetual snow, as in many of the South American volcanoes, the fearful deluges produced by the sudden melting of the snows are often the most destructive phenomenon connected with the eruption.

Volcanic eruptions, therefore, may be divided into two great types, viz., the *quiet* and the *explosive.* In the one, lava-flows predominate; in the other, cinders and ashes, and steam and gas. The Hawaiian volcanoes are perhaps the best examples of the former, and the Javanese volcanoes, especially Krakatoa, of the latter. The Mediterranean and most other volcanoes are mixtures of these two types in varying proportions.

The quantity of materials ejected during an eruption is sometimes almost inconceivable. During the great eruption of Tomboro, already mentioned, ashes and cinders were ejected sufficient to make three

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* Dana's Manual, p. 692.

† Judd, Nature, vol. xxxviii, p. 540, 1888.

‡ Lyell, Principles of Geology.

# Science, vol. iv, p. 134, 1884.

Mont Blancs, or to cover the whole of Germany two feet deep, or equal to 37 cubic miles.* In the eruption of Krakatoa, August, 1883, 4½ cubic miles of material were blown into dust so fine that it was carried by the gas-current 17 miles high, and some of it remained suspended for two or three years. The lava which streamed from Skaptar Jökull, Iceland, in 1783, has been computed to be equivalent to about twenty-one cubic miles, or to the whole quantity of water poured by the Nile into the sea in one year! These were, however, very extraordinary eruptions. In the greatest eruptions of Vesuvius the quantity of lava poured out was not more than 600,000,000 cubic feet = one square mile covered twenty-two feet deep. The volume of lava poured out by Kilauea, in 1840, is estimated by Dana as sufficient to cover one square mile of surface 800 feet deep.

Great destruction of life is often produced by volcanic eruptions. The overthrow of Herculaneum and Pompeii by ejections from Vesuvius is well known. The great eruption of Skaptar Jökull destroyed 1,300 human lives and 150,000 domestic animals. The eruption of Etna, in 1669, overwhelmed fourteen towns and villages. In the province of Tomboro, out of a population of 12,000, only twenty-six persons escaped the great eruption of 1815.

Monticules.—Eruptions occur not only from the summit-crater, but also frequently from fissures in the side of the mountain. By the immense upheaving force necessary to raise lava to the mouth of the crater of a lofty volcano, the mountain is fissured by cracks radiating from the crater in all directions. These cracks are filled with lava, which on hardening form radiating dikes which intersect the successive layers of ejections, and bind them into a stronger mass (Fig. 78, p. 96). Through these fissures the principal streams of lava often pass. During an eruption of Mauna Loa, in 1852, the immense pressure of the lava in the principal crater fissured the side of the mountain, and a fiery fountain of liquid lava, 1,000 feet wide, was projected upward through the fissure to the height of 700 feet, and continued to play for several days. Upon these fissures subordinate craters, and finally cones, are formed. These subordinate cones about the base, and upon the slopes of the principal cone, are called *monticules* or *hornitos*. There are about 600 monticules on Etna—one of them over 700 feet high (Jukes).

Materials erupted.—As we have already stated, the materials erupted are *stones*, *lava-streams*, *cinders*, *ashes*, and *gases*.

Stones.—In explosive eruptions the solid floor of the crater is often blown out with violence, and rock-fragments, sometimes of vast size, are thrown to great distances.

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* Herschel, Physical Geology, p. 111.

Lava.—The term *lava* is applied to the liquid matter poured from a volcano during eruption, and also to the same when it has hardened into rock.

Liquidity of Lava.—At the time of eruption the liquidity of lava varies very much, depending partly upon the *heat*, partly on the *fusibility* of the material, and partly upon the *kind of fusion.* In the Hawaiian volcanoes the lava is a melted glass almost as thin as honey. In Kilauea this lava is often thrown into the air by the bursting of gas-bubbles, and drawn out into long threads like spun glass, which is carried by the winds, and collects in places as a soft, brownish, towy mass, called "*Pélê's hair.*"

Physical Conditions of Lava.—Completely fused lava, when cooled rapidly, forms volcanic slag or volcanic glass (*obsidian*); but if cooled slowly, so that the several minerals of which it is composed have time to separate and crystallize, forms *stony lava.* If it is full of gas-bubbles (*rock-froth*) and hardens in this condition, it forms *veeicnlar* or *scoriaceous lava.* If the quantity of gas and steam be very great, the whole liquid mass may swell into a *rock-froth*, which rises to the lip of the crater, and outpours much as porter or ale from a bottle when the cork is drawn. Or the rock-forth may be thrown violently into the air, and, hardening there, may fall again in *cindery* or *scoriaceous* masses; or, thrown with still greater violence, the rock-froth may be broken into fine *rock-spray*, and fall as *volcanic sand and ashes.* Ashes, when consolidated by time and percolating water, or when deposited in water form *tufa.* Thus, there are four physical conditions in which we find lava—viz., *stony*, *glassy*, *scoriaceous*, and *tufaceous.*

Again, the liquidity of lava and its character depend much on the *kind of fusion.* Daubrée has shown that all siliceous rocks and glass mixtures, in the presence of *superheated water* even in small quantities, and under pressure, will become more or less liquid, at temperatures far below that necessary to produce true fusion. At 400° Fahr., such rocks become pasty, at 800° completely liquid. The same change takes place at even lower temperatures if a little alkali be present. To distinguish this liquidity from that of true igneous fusion, which requires a temperature of 2,500° to 3,000°, it has been called *aqueo-igneous* or *hydrothermal fusion.* Now, very much lava at the time of eruption is in this condition. Such lava, when the pressure is suddenly removed by breaking up of the floor of the crater, and the contained water suddenly changed into steam, is blown into the finest *dust*, which is then carried to great height by the out-rushing steam, and falls again as *volcanic ashes*, which may consolidate into tufa. If the heat be not sufficient to produce complete aqueo-igneous fusion, the lava is outpoured as a kind of *rock-broth* consisting of unfused particles in a semifused mass, which concretes into an *earthy* kind of rock. Or the material may pour out only as hot mud, which concretes into a kind of *tufa*. In fact, every variety of fusion and semifusion, depending on the degree of heat and the quantity of water, may be traced, from perfect igneous fusion through various grades of aqueo-igneous fusion, to the condition of hot mud.

It is evident that, of the two *kinds of eruption* mentioned above, the quiet type is characterized by igneous fusion, the explosive type by aqueo-igneous fusion. In the former the heat is great, but the amount of water is small; while in the latter the heat is less, but the amount of water far greater.

The rapidity of the flow of a lava-stream depends on its fluidity. In the Hawaiian volcanoes the lava, where it issues from the crater, has been seen to flow with a velocity of fifteen miles an hour; while Vesuvian lava seldom flows at a rate of more than two or three miles an hour. Lava, like glass, passes through various grades of viccous fluidity in cooling. It gradually becomes so stiff that it may flow only a few feet per day. The froth or scum which covers the surface of a lava-stream quickly cools and hardens into a crust of vesicular lava, which may even be walked upon while the interior is still flowing beneath. In this way are often formed long *galleries*. Also the running together of the contained gas-bubbles and steam-bubbles forms huge blisters in the viscous mass, which, on hardening, form cavities often of great size. Thus, recent lavas have often a cavernous and galleried structure, like limestone (page 77), but from a different cause.

Classification of Lavas.—*Mineralogically*, lava consists essentially of feldspar, augite, and magnetite, either their constituents chemically united, as in glassy lava, or aggregated into more or less distinct particles or crystals, as in the stony varieties. Now, feldspar is a light-colored mineral, having a specific gravity of about 2·5, while augite and magnetite are usually very dark-colored minerals, having specific gravities of about 3·5 to 5. It is evident, therefore, that in proportion as feldspar predominates, the lava is lighter colored and of less specific gravity; and in proportion as augite and magnetite predominate, the rock is darker and heavier. Chemically, feldspar is a silicate of alumina and alkali, with excess of silica (acid silicate). The alkali may be either potash, and then it is called *potash feldspar*, or *orthoclase;* or else it is soda and lime, and then it is called *soda-lime feldspar*, or *plagioclase*. Of these two the former is the more acid. Augite is a silicate of lime, magnesia, and iron, with excess of base (basic silicate). Therefore, lava may be divided into two classes—*acidic lavas* and *basic lavas*. In the former, feldspar predominates, in the latter augite. Moreover, in the one the form of feldspar is orthoclase, in the other plagioclase. Further, it is seen that all lavas are *multiple silicates*, like glass: they are, therefore, true glass-mixtures. Now, the acidic lavas are a more difficultly fusible, the basic lavas a more easily fusible glass-mixture. Either of these two kinds of lava may exist in any of the conditions mentioned above —viz., as stony, glassy, vesicular, or tufaceous lava. *Trachyte* is an example of acidic lava, and *basalt* of basic lava in a stony condition. *Pumice* is a peculiar vesicular variety of feldspathic lava.

It is not improbable that the fusion and subsequent cooling of granite, or gneiss, or even of the purer varieties of mixed sandstones and clays, would make a *trachytic* lava; while the fusion and cooling of impure slates and shales and limestones would produce *basaltic* lava.

Gas, Smoke, and Flame.—The gases emitted by volcanoes are principally *steam*, *sulphurous vapor* (S and SO_2), *hydrochloric acid*, and *carbonic acid*. By far the most abundant of these is steam. In violent, explosive eruptions, which eject principally cinders and ashes, it is probable that water, mostly in the form of steam, is one of the most abundant of all the ejected materials. In quiet lava-eruptions, like those of the Hawaiian volcanoes, the quantity of steam and gases is small. It is worthy of notice, in connection with the position of volcanoes near the sea, that the gases ejected are such as might be formed from sea-water and from limestone. The so-called *smoke* and *flame* of volcanoes have no connection with combustion. The condensed vapors and the ashes suspended in the air, often in such quantities as to make midnight-darkness at high noon, form the smoke; and the red glare of the same, reflecting the light from the incandescent lava beneath, forms the apparent flame.

All volcanic ejections, except the gases, accumulate about the crater, and continue to increase with every successive eruption, forming a sort of *stratified* deposit. Sometimes the cone is made up of successive layers of lava, as in Hawaiian volcanoes; sometimes it is made up of successive layers of cinders or tufa; sometimes of alternate layers of lava and tufa. Stratified materials of this kind, however, can not be confounded with those produced by the action of water. In the former case the stratification is not the result of the *sorting* of the materials.

Kinds of Volcanic Cones.—Volcanic cones and craters have been divided into two kinds—viz., *cones of elevation* and *cones of eruption*. A cone of elevation is formed by interior forces lifting the crust of the earth at a particular point until the latter breaks and forms a crater, through which eruptions take place. It is an *earth-blister*, which swells and breaks at the top. A cone of eruption, on the other hand, is formed by the accumulation around a crater of its own ejection. There has been much discussion among physical geologists as to whether existing volcanic cones are formed mostly by the one method or the other. We will not enter into this discussion. It seems probable, however, that most cones are principally cones of eruption, although their height and size have been increased somewhat also by elevating forces.

Mode of Formation of a Volcanic Cone.—A volcano commences—1. As a simple opening in the earth's crust, in most cases with little or no elevation. Through this opening or crater are ejected, from time to time, lava, cinders, ashes, etc., which accumulate immediately about the crater, and continue to increase, by successive layers, with every eruption. Ejections of pure lava, particularly if the lava is very fluid, form a cone of broad base and low inclination. This is the case with the Pacific volcanoes. Fig. 76 is a section through Hawaii, showing the slope of the pure lava-cones of Mauna Loa (*L*), nearly 14,000 feet high, and of Mauna Kea (*K*). Tufa-cones and cinder-cones (Fig. 77) take a much higher angle

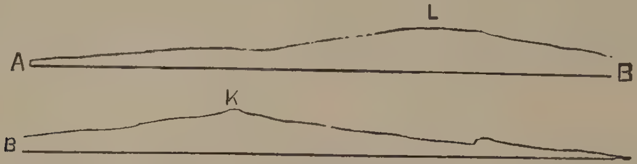


FIG. 76.—Section across Hawaii.

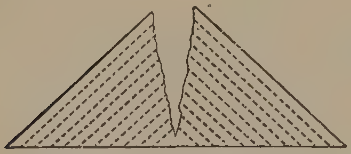


FIG. 77.—Section of Cinder-Cone.

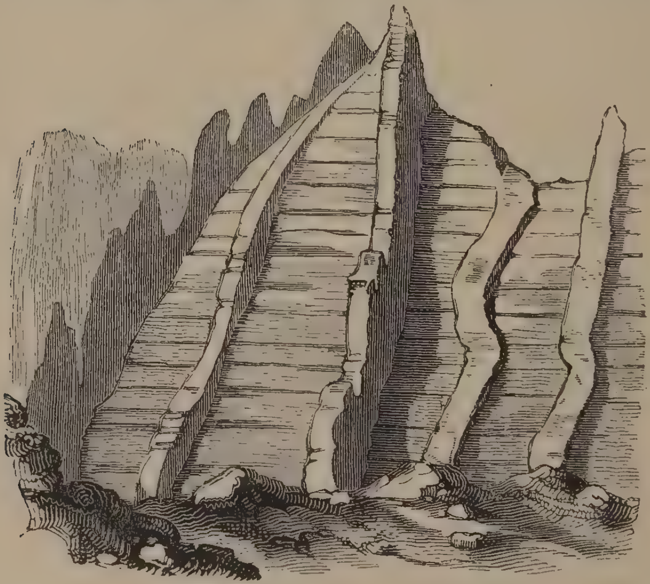


FIG. 78.—Dikes at the Base of the Serra del Solfizio, Etna.

of slope. 2. With every eruption the powerful internal forces fissure the mountain, in lines radiating from the crater. These fissures are filled with liquid lava, which, on hardening, forms *radiating dikes*, intersecting the layers of ejections, and binding them into a more solid mass. By erosion these stand out from the sides of the mountain like buttresses. Fig. 78 shows how these dikes, rendered more visible by erosion, intersect the strata. 3. After a time, when the mountain has grown to considerable height, the force necessary to raise liquid lava to the lip of the crater becomes so great that it breaks in preference through the fissured sides of the mountain. The secondary craters thus formed immediately commence to make accumulations around themselves, and thus form *secondary cones* (Fig. 79, c'), or monticules, about the base and on the sides of the primary cone. If a secondary cone becomes extinct, it is finally buried (Fig. 79, c'') in the layers of the primary cone. 4. Finally, in volcanoes of the explosive type, during great eruptions the whole top of the mountain is often blown off, and in volcanoes of the quieter type is melted and falls in—in either case forming an immense crater, within which, by subsequent eruptions, another smaller cone of eruption is built up, and in this latter often a still smaller cone is again built. This *cone-within-cone* structure is well illustrated by the present condition, and still better by the history, of Vesuvius. Vesuvius is a double-peaked mountain, with a deep, semicircular valley between the peaks. The present active cone of Vesuvius is encircled by a rampart, very high

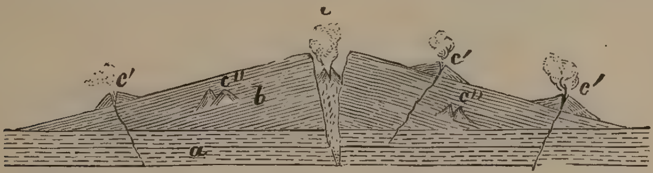
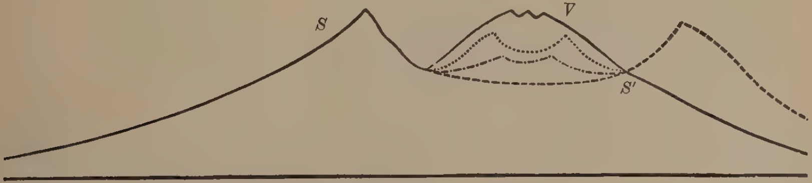


FIG. 79.—Section of Volcano, showing Monticules.



——— Present outline of Vesuvius and Somma.
- - - - - Outline of the volcano before the great eruption of 79.
—-—-— Outline of the cone during the sixteenth and seventeenth centuries.
·········· Outline of the cone after the great eruption of 1822.

FIG. 80.—Outlines of Vesuvius, showing its form at different periods of its history (after Judd).

on one side, and called Mount Somma, but traceable to some degree all around, and having the same structure as Vesuvius itself. This rampart is the remains of a great crater, many miles in diameter. Fig. 80 is an ideal section through Mount Somma (*S*), and Vesuvius (*V*). *S′* is the almost obliterated remains of the old crater on the other side.

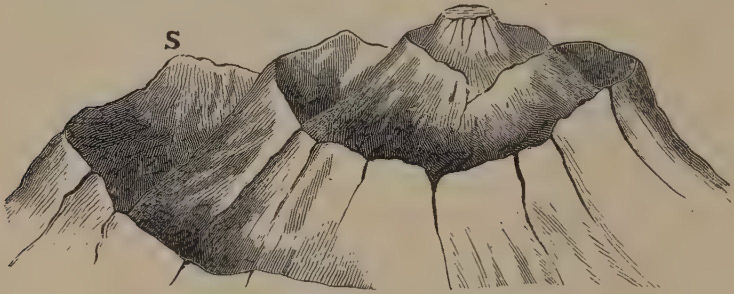


Fig. 81.—Mount Vesuvius in 1756 (after Scrope.)

This is further and beautifully illustrated by the history of this mountain, which records the repeated destruction and rebuilding of these cones within cones. Fig. 81 is an outline of Vesuvius as it existed in 1756;* *S* is Mount Somma.

Many other volcanoes are known which have similar circular ramparts made up of layers of volcanic ejections. One of the most remarkable of these is Barren Island, in the Bay of Bengal (Fig. 82). The difference between this and Vesuvius is, that the circle is more complete.†

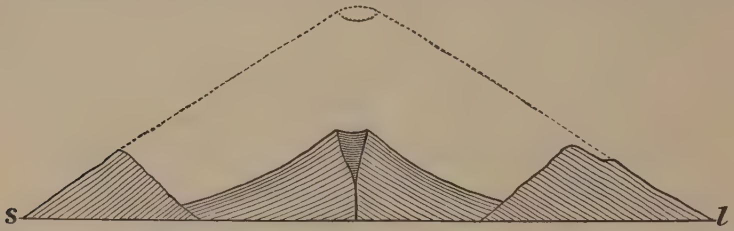


Fig. 82.—Section across Barren Island (after Mallett): *s l*, sea-level. The dotted line is added to show the supposed former conditions.

Comparison between a Volcanic Cone and an Exogenous Tree.—It is evident, then, that a cone of eruption grows by layers successively applied on the outside. Both in structure and growth it may, therefore, be compared to an exogenous tree: 1. As the sap ascends through the center of the shoot and descends on the outside, forming layers of wood, one outside of the other, increasing every year the height and the diameter of the tree; so in a volcano lava ascends through the center and pours over the outside, forming also successive layers, increasing both the diameter and the height. 2. As a cross-section of a tree shows concentric *rings* around (Fig. 83) a central *pith*, and is traversed by *pith-rays;* so a cross-section of a volcano would show a central crater, with concentric layers, traversed by radiating dikes. 3. As on the pith-rays, where they emerge upon the surface, arise *buds*, which grow in a manner similar to the trunk; so on the radiating dikes are formed monticules, which grow like the principal cone. If buds die, they are covered up in the annual layers of the trunk; so, in like manner, extinct monticules are buried in the layers of the principal cone.

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* Scrope, Philosophical Magazine, vol. xiv, p. 139.

† Medlicot and Blandford, Manual of Geology of India, p. 736.

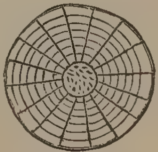

FIG. 83.

Estimate of the Age of Volcanoes.—The age of exogenous trees, as is well known, may be estimated by counting the annual rings. The age of volcanoes can not be estimated accurately in a similar manner: 1. Because the overflows are not regularly periodical; 2. Because in the case of lava-overflows it requires many overflows to make one complete layer; and, 3. Because it is impossible to make a complete section of the mountain. Nevertheless, Nature gives us partial sections, which reveal an almost incalculable antiquity. Thus, the Val de Bové, of Etna (a huge valley reaching from near the summit to the foot, and probably formed by an ingulfment of a portion of the mountain), gives a perpendicular section into the heart of the mountain 3,000 feet deep. Throughout the whole of this section the mountain is composed entirely of layers of lava and cinders. It is almost certain, therefore, that the whole mountain to its very base, 11,000 feet, is similarly composed. That the time necessary to accumulate this immense pile, 11,000 feet high and ninety miles in circumference at the base, was almost inconceivably great, is shown by the fact that Etna had already attained very nearly its present size and shape 2,500 years ago, when it was observed by the early Greek writers. The lava-stream which stopped the Carthaginians in their march against Syracuse, 396 years before Christ, may still be seen *at the surface*, not yet covered by subsequent eruptions. And yet Etna belongs to the most recent geological epoch, for it has broken through, and is built upon, the newer tertiary strata.

Theory of Volcanoes.

In the theory of volcanoes there are two things to be accounted for, viz.: 1. The *force* necessary to raise melted lava to the lips of the crater, and even to project it with violence high into the air; 2. The *heat* necessary to fuse rocks and form lava.

Force.—The specific gravity of lava being about 2·5 to 3, it would require the pressure of one atmosphere, or fifteen pounds to the square inch, for every eleven or twelve feet of vertical elevation of the liquid mass. The following table gives the pressure in atmospheres for four well-known volcanoes, assuming the point of hydrostatic equilibrium to be at the sea-level:

NAME.	Height.	Pressure in atmospheres.
Vesuvius	3,900 feet	325
Etna	11,000 "	920
Mauna Loa	13,800 "	1,150
Cotopaxi	19,660 "	1,638

The lava is often, however, in a frothy or vesicular condition. In such cases the pressure necessary to produce overflow would be much less. But, on the other hand, the force in most cases is not only sufficient to lift lava to the top of the crater, but to project it thousands of feet in the air. A rock-mass of over 2,700 cubic feet was projected from the crater of Cotopaxi to a distance of nine miles (Lyell). The *agent* of this prodigious force is evidently gas and vapors, especially steam. The great quantity of steam issuing from all volcanoes, but especially from those of the explosive type, is sufficient proof. Thus far theorists generally agree, but from this point opinions diverge into the most opposite directions.

The Heat.—There are many and diverse opinions as to the source of the heat associated with volcanic eruptions. Two prominent views, however, may be said to divide geologists. According to the *one*, the heat is the remains of the *primal* heat of the once universally incandescent earth; according to the other, the heat is produced by *chemical* or *mechanical* action. According to the former, the heat is general, and only the access of water is local; according to the latter, both the heat and the access of water are local. According to the former, volcanoes are openings through the comparatively thin crust, revealing the universal interior fluid; according to the latter, they are openings into isolated interior lakes of molten matter. The former may be called the "interior fluidity" theory; the latter divides into two branches, which may be called respectively the "chemical" and the "mechanical" theory. In all, access of water to the hot interior furnishes the force.

Internal Fluidity Theory.—This theory supposes that the earth, from its original incandescent condition, slowly cooled and formed a surface-crust; that this surface-crust, though ever thickening by additions to its interior surface, is still comparatively very thin, and beneath it is still the universal incandescent liquid; that by movements of the surface the solid crust is fissured, and water from the sea or from other sources finds its way to the incandescent liquid mass, and develops elastic force sufficient to produce eruption.

By this view the focus of volcanoes is situated at the lower limit of the solid crust. The theory seems clear and simple enough, but when closely examined there are many difficulties in the way of its acceptance.

Objections.—The objections to this view are: 1. That the crust, as already shown, must be far thicker than this theory requires, probably hundreds of miles thick, if, indeed, there be any general liquid interior at all; but volcanoes are evidently very superficial phenomena. Under the pressure of this difficulty these theorists have been driven to the acknowledgment of *local thinnings* of the solid crust in the region of volcanoes.

2. Pressure on a general interior liquid from any cause at any place would, by the law of hydrostatics, be transmitted equally to every part of the crust, which would, therefore, yield at the weakest point, wherever that may be, even though it be on the opposite side of the globe; but the force of volcanic eruption is evidently just beneath the volcano.

3. Volcanoes belonging to the same group, and therefore near together, often erupt independently, as if each had its own reservoir of liquid matter. The pressure of these two objections has driven many to the admission of a sort of *honey-combed remains* of the interior liquid inclosed in the solid crust, and now isolated both from the interior liquid and from each other.

Chemical Theory.—Whether or not the earth consist of solid crust covering an interior liquid, it almost certainly consists of an *oxidized crust* covering an *unoxidized interior.* Now, the oxidizing agents are water and air, and therefore the limit of the oxidized crust is the limit of volcanic water. Therefore, the oxidizing agent and the unoxidized material are in close proximity, and the former ever encroaching on the later, and therefore liable at any moment to set up chemical action, the intensity of which would vary with the nature of the material. If the action be intense, heat may be formed sufficient to fuse the rocks and to develop elastic force necessary to produce eruption.

In this general form, the chemical theory seems plausible, but many have attempted to give it more definiteness, and to explain the special forms of oxidization which cause volcanoes. The most celebrated of these definite forms is that of Sir Humphry Davy, who attributed it to the contact of water with metallic potassium, sodium, calcium, and magnesium, in the interior of the earth. In such definite forms the theory seems far too hypothetical.

Recent Theories.—1. *Aqueo-igneous Theory.*—Accumulation of sediment on sea-bottoms would necessarily produce corresponding rise of isogeotherms, and thus the interior heat of the earth would invade the sediments with their contained waters. The lower portion of sediments 10,000 feet thick would be raised to a temperature of about 260° Fahr., and of 40,000 feet thick (sediments of this thickness and more are known) to that of 860°. This temperature, or even a less temperature if alkali be present, would be sufficient in the presence of the contained water of the sediments to produce complete aqueo-igneous fusion, and probably to develop elastic force sufficient to produce eruption. This view was first brought forward by John Herschel. Observe that this temperature and the corresponding force would be gradually developed as the accumulation progressed, until sufficient to produce these effects. Observe, again, that in this case the water does not seek the heat by *descending* (the difficulties in the way of this are insuperable), but the heat seeks the already imprisoned water by *ascending*.

It seems very probable that cases of eruption of hot mud and of aqueo-igneously fused lavas may be accounted for in this way, but the temperature would not be sufficient to account for true igneous fusion, nor would the force be sufficient to break up the crust of the earth and produce eruption. It is possible, however, that this may be combined with the next theory.

2. *Mechanical Theory.*—As we shall explain hereafter (p. 274), there is much reason to believe that the interior of the earth is contracting more rapidly than the exterior, and that the exterior is thus necessarily thrust upon itself by irresistible horizontal pressure. According to Mr. Mallet, the crushing of the rocky crust in places under this pressure develops heat sufficient to fuse the rocks, and to produce eruption. But it is at least doubtful whether the heat thus generated would *alone* be sufficient for this purpose.

3. *Issuing of Superheated Gases.*—Rev. O. Fisher has advanced a view which deserves attention. He thinks volcanoes are vents through which issue from the earth's interior superheated steam and gases, melting the rocks in their course and ejecting them by their pressure. According to this view, the water is not derived from the surface, but is original and constituent. This view is independent of the condition of the earth's interior, whether solid or liquid; for a temperature which would permit solidity at great depths would produce fusion under less pressure near the surface.* The sun may be regarded as a globe in an earlier and more active stage of vulcanism. From its interior gases are seen to issue in great quantity, and almost constantly.

4. *Prestwich's Theory.*—If we assume the existence of a sub-crust layer of liquid matter, then lateral crushing of the earth's crust, such

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* Cambridge Philosophical Society, 1875.

as undoubtedly occurs in mountain-making, would squeeze the liquid upward into and through fissures to the surface, producing the *quieter* lava-eruptions; or else, coming in contact in its upward course with subterranean waters, especially abundant in the fissured and cavernous structure of recent lavas, would develop steam and therefore violent *explosive eruptions.*

5. *Fusion by relief of Pressure.*—We have already seen that there is probably a sub-crust layer, which if not fused is nearest the fusing-point, and therefore liable to become fused not by increase of heat, but by relief of pressure. Such relief of pressure may be produced either by erosion, which often cuts away miles of thickness, or by a fissure, or by lateral pressure such as elevates mountain-ranges. In the last case the same lateral crush, which by relief of pressure produced the fusion, would also squeeze out the liquid matter thus formed.

Subordinate Volcanic Phenomena.

These are *hot springs*, *carbonated springs*, *solfataras*, *fumaroles*, *mud-volcanoes*, and *geysers.* They are all *secondary* phenomena, i. e., formed by the percolation of meteoric water through hot volcanic ejections. Or perhaps in some cases the heat may be produced by slow rock-crushing by horizontal pressure, as explained above, or else by local chemical action.

General Explanation.—Thick masses of lava outpoured from volcanoes remain hot in their interior for an incalculable time. Water percolating through these acquires their heat, and comes up again as hot springs; or, if in addition it contains lime, as lime-depositing springs; or, if it contains carbonic acid, as carbonated springs; or, if it contains sulphurous acid and sulphureted hydrogen, as solfataras. If condensible vapors issue in abundance so as to make an appearance of smoke, they are called fumaroles. If the hot water brings up with it mud which accumulates about the vent, then it is a mud-spring or a mud-volcano. If the heat is very great, so that violent eruption of water takes place periodically, then it becomes a geyser. We have already spoken of carbonated lime-depositing springs (p. 78). We shall again, under the head of the theory of mineral veins (p. 243), speak of solfataras. The only one which need detain us now is geysers.

Geysers.

A geyser may be defined as a *periodically eruptive spring.* Geysers are found only in Iceland, in the Yellowstone Park of the United States, and in New Zealand. The so-called geysers of California are rather fumaroles. Those of Iceland have been long studied; we will, therefore, describe these first.

Iceland is a volcanic plateau, with a narrow marginal habitable region sloping gently to the sea. The interior plateau is the seat of every species of volcanic action, viz., lava-eruptions, solfataras, mud-volcanoes, hot springs, and geysers. There are several hundred vents of all kinds in comparatively small space, among which are many geysers. One of these, the *Great Geyser,* has long attracted attention.

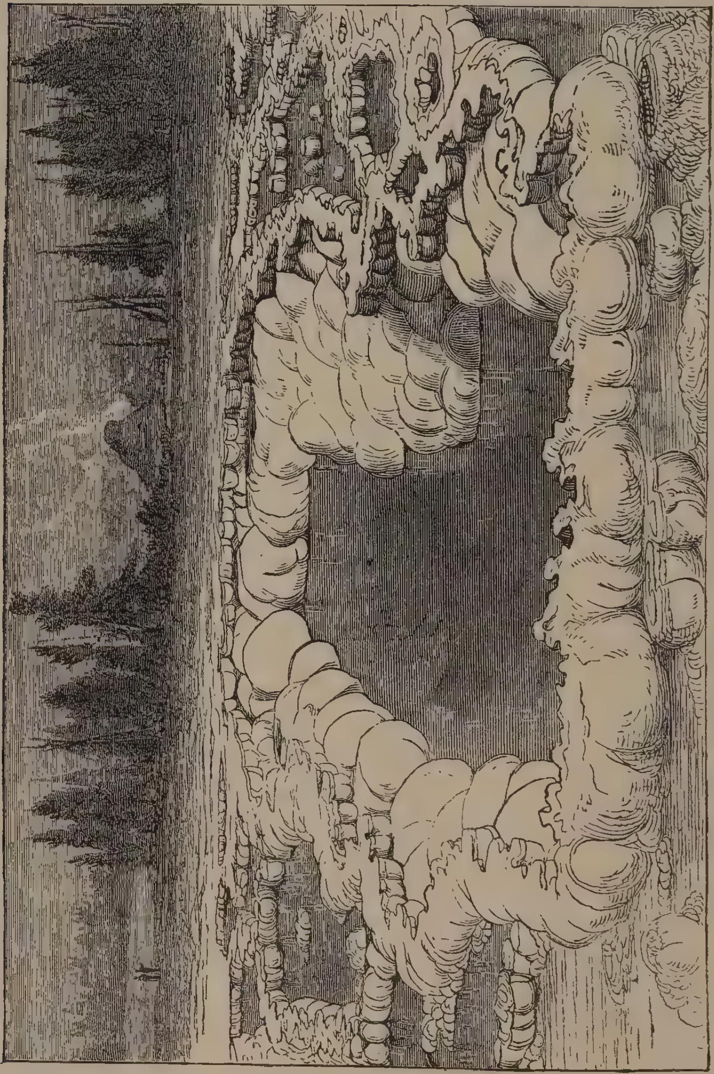

Fig. 84.—Geyser near the Giant showing the Ornamental Character of the Border (after Hayden).

Description.—The Great Geyser is a basin or pool fifty-six feet in diameter, on the top of a mound thirty feet high. From the bottom of the basin descends a funnel-shaped pipe eight or ten feet in diameter, and seventy-eight feet deep. Both the basin and the tube are lined with silica, evidently deposited from the water. The natural inference is, that the mound is built up by deposit from the water, in somewhat the same manner as a volcanic cone is built up by its own ejections. In the intervals between the eruptions the basin is filled to the brim with perfectly transparent water, having a temperature of about 170° to 180°.

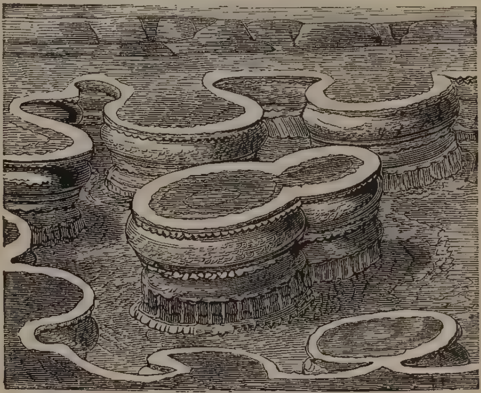
Fig. 85.—(After Hayden.)

Phenomena of an Eruption.—1. Immediately preceding the eruptions sounds like cannonading are heard beneath, and bubbles rise and break on the surface of the water. 2. A bulging of the surface is then seen, and the water overflows the basin. 3. Immediately thereafter the whole of the water in the tube and basin is shot upward one hundred feet high, forming a fountain of dazzling splendor. 4. The eruption of water is immediately followed by the escape of steam with a roaring noise. These last two phenomena are repeated several times, so that the fountain continues to play for several minutes, until the water is sufficiently cooled, and then all is again quiet until another eruption. The level of the water after an eruption is seven or eight feet in the tube. The

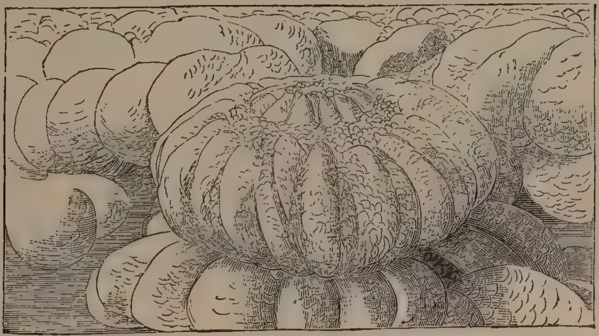
Fig. 86.—The Turban (after Hayden).

frequency of the eruptions is slowly diminishing. In 1804 it was once every hour; now several days often elapse.* Throwing large stones into the tube has the effect of bringing on the eruption more quickly.

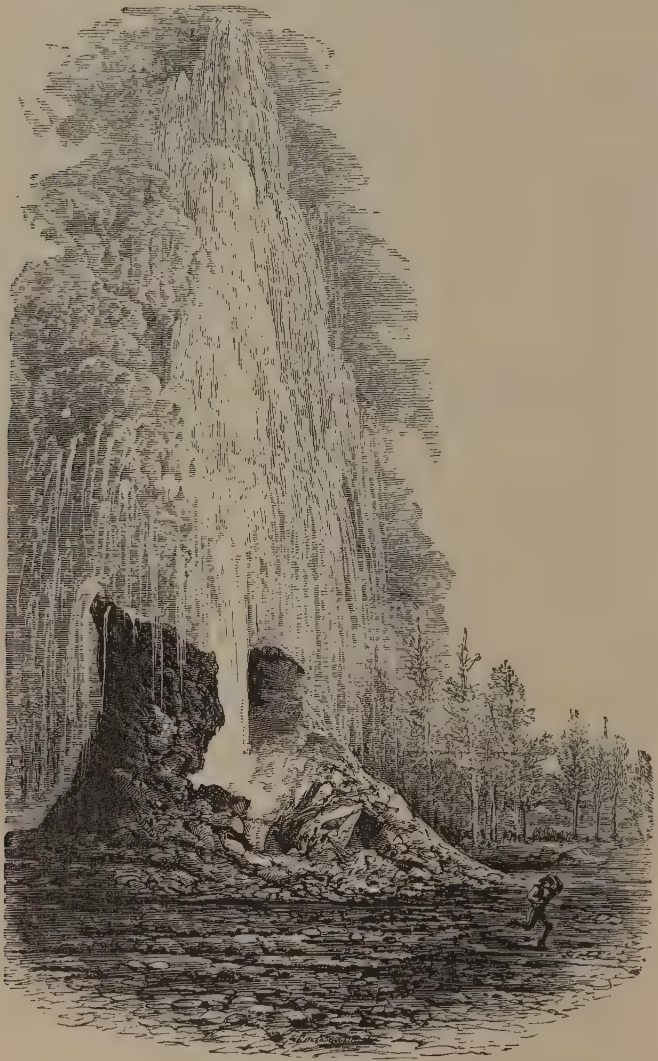

FIG. 87.—Giant Geyser (after Hayden).

Yellowstone Geysers.—In magnificence of geyser displays, however, Iceland is far surpassed by the geyser basin of Firehole River. This wonderful geyser region is situated in the northwest corner of Wyoming, on an elevated volcanic plateau near the head-waters of the Madison River, a tributary of the Missouri, and of the Snake River, a tributary of the Columbia. The basin is only about three miles wide. About it are abundant evidences of prodigious volcanic activity in former times, and although primary volcanic activity has ceased, secondary volcanic phenomena are developed on a stupendous scale and of every kind, viz.: hot springs, carbonated springs, fumaroles, mud-volcanoes, and geysers. In the Yellowstone Park itself there are at least 3,000 vents of all kinds, and of these more than sixty are erup-

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* Daubrée, Archives des Sciences, vol. xix, p. 425, 1888.

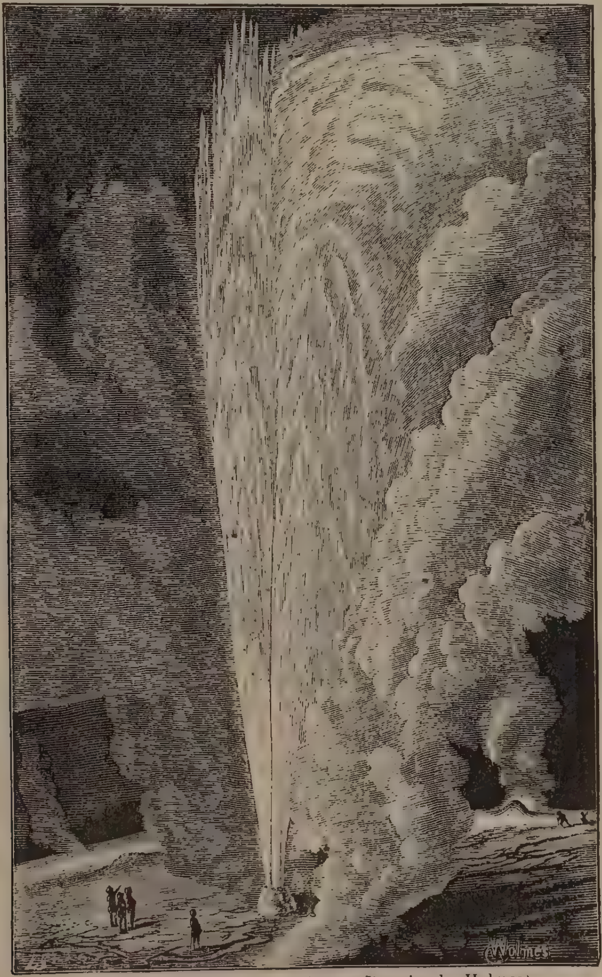

FIG. 88. –Bee-Hive Geyser (from a Drawing by Holmes).

tive geysers. In some places, as on Gardiner's River, the hot springs are mostly lime-depositing (page 78); in others, as on Firehole River, they are geysers depositing silica.

In the upper geyser basin the valley is covered with a snowy deposit from the hot geyser-waters. The surface of the mound-like, chimney-like, and hive-like elevations (Fig. 89), immediately surrounding the vents, is, in some cases, ornamented in the most exquisite manner by deposits of the same, in the form of scalloped embroidery set with pearly tubercles; in others the siliceous deposits take the most fantastic forms (Figs. 84, 85, 86). In some places the silica is deposited in large quantities, three or four inches deep, in a gelatinous condition like starch-paste. Trunks and branches of trees immersed in these waters are speedily petrified. It has been shown by Mr. Weed that the process is greatly assisted by the growth of certain algæ.*

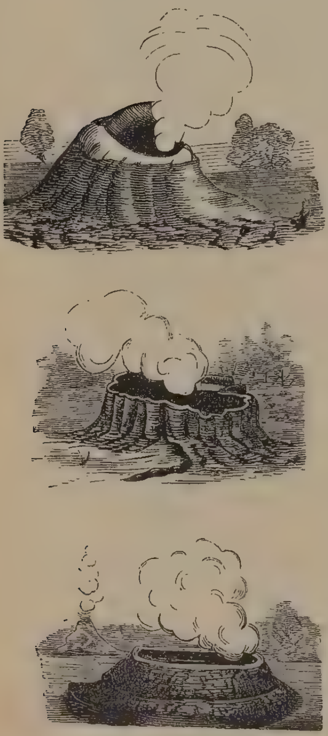

FIG. 89.—Forms of Geyser-Craters (after Hayden).

We can only mention a few of the grandest of these geysers:

1. The "Grand Geyser," according to Hayden, throws up a column of water six feet in diameter to the height of 200 feet, while the steam ascends 1,000 feet or more. The eruption is repeated every thirty-two hours, and lasts twenty minutes. In a state of quiescence the temperature of the water at the surface is about 150°.

2. The "Giantess" throws up a large column twenty feet in diameter to a height of sixty feet, and through this great mass it shoots up five or six lesser jets to a height of 250 feet. Its eruptions are fitful but last sometimes several hours.

3. The "Giant" (Fig. 87) throws a column five feet in diameter 140 feet high, and plays continuously for three hours.

4. The "Bee-Hive" (Fig. 88), so called from the shape of its mound, shoots up a splendid column two or three feet in diameter to the height by measurement of 219 feet, and plays fifteen minutes.

5. "Old Faithful," so called from the frequency and regularity of its eruptions, throws up a column six feet in diameter to the height of 100 to 150 feet regularly every hour, and plays each time fifteen minutes.

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* Am. Jour., vol. xxxvii, p. 351, 1889.

Theories of Geyser-Eruption.—The water of geysers is not volcanic water, but simple spring-water. A geyser is not, therefore, a volcano ejecting water, but a true spring. There has been much speculation concerning the cause of their truly wonderful eruptions.

Mackenzie's Theory.—According to Mackenzie, the eruptions of the Great Geyser may be accounted for by supposing its pipe connected by a narrow conduit with the lower part of a subterranean cave, whose walls are heated by the near vicinity of volcanic fires. Fig. 90 represents a section through the basin, tube, and supposed cave. Now, if meteoric water should run into the cave through fissures more rapidly than it can evaporate, it would accumulate until it rose above, and therefore closed, the opening at *a*. The steam, now having no outlet, would condense in the chamber *b* until its pressure raised the water into the pipe, and caused it to overflow the basin. The pressure still continuing, all the water would be driven out of the cave, and partly up the pipe. Now, the pressure which sustained the whole column *a d* would not only sustain, but eject with violence, the column *c d*. The steam would escape, the ejected water would cool, and a period of quiescence would follow. If there were but one geyser in Iceland, this would be rightly considered a very ingenious and probable hypothesis, for without doubt we may conceive of a cave and conduit so constructed as to account for the phenomena. But there are many eruptive springs in Iceland, and it is inconceivable that all of them should have caves and conduits so peculiarly constructed. This theory is therefore entirely untenable.

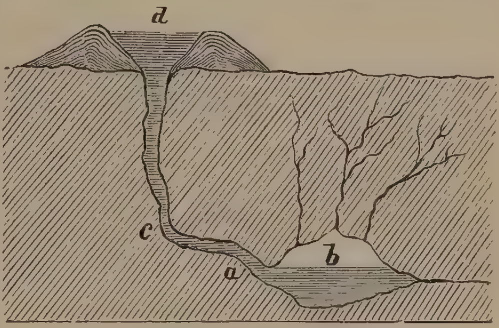

FIG. 90.—Mackenzie's Theory of Eruption.

Bunsen's Investigations.—The investigations of Bunsen and his theory of the eruption and the formation of geysers are among the most beautiful illustrations of scientific induction which we have in geology. We therefore give it, perhaps, more fully than its strict geological importance warrants.

Bunsen examined all the phenomena of hot springs in Iceland. 1. He ascertained that geyser-water is meteoric water, containing the soluble matters of the igneous rocks in the vicinity. He formed identical water by digesting Iceland rocks in hot rain-water. 2. He ascertained that there are two kinds of hot springs in Iceland, viz., *acid* *springs* and *alkaline-carbonate springs*, and that only alkaline-carbonate springs contain any silica in solution. The reason is obvious; alkaline waters, especially if hot, are the natural solvents of silica. 3. He ascertained that *only the silicated springs form geysers.* Here is one important step taken—one condition of geyser-formation discovered. Deposit of silica is necessary to the existence of geysers. The tube of a geyser is not an accidental conduit, but is built up by its own deposit. 4. Of silicated springs, *only those with deep tubes erupt*—another condition. 5. Contrary to previous opinion, the silica in solution does not deposit on cooling, but only by drying. This would make the building-up of a geyser-tube an inconceivably slow process, and the time proportionally long. 6. The temperature of the water in the basin was found to be usually 170° to 180°, and that in the tube to increase rapidly, though not regularly, with depth. Moreover, the temperature, both at the surface and at all depths, increased regularly as the time of eruption approached. Just before the eruption it was, at the depth of about forty-five feet, very near the boiling-point *for that depth.*

Theory of Geyser-Eruption—Principles.—1. It is well known that the boiling-point of water rises as the pressure increases. This is shown in the adjoining table. 2. It follows from the above that if water be under strong pressure, and at high temperature, though below its boiling-point for that pressure, and the pressure be diminished sufficiently, it will immediately flash into steam. 3. Water heated beneath, if the circulation be unimpeded, is *very nearly* the same temperature, throughout. That it is never the same temperature precisely is shown by the circulation itself, which is caused by difference of temperature, producing difference in density. The phenomenon of simmering is also a well-known evidence of this difference of temperature, since it is produced by the collapse of steam-bubbles rising into the cooler water above. 4. But if the circulation be *impeded*, as when the water is contained in long, narrow, irregular tubes, and heated with great rapidity, the temperature may be greater below than above to any extent, and the boiling-point may be reached in the lower part of the tube, while it is far from this point in the upper part.

Pressure in Atmospheres.	Boiling-Point.
1 Atmos.	212°
2 "	250°
3 "	275°
4 "	293°

Application to Geysers.—We will suppose a geyser to have a simple but irregular tube, without a cave, heated below by volcanic fires, or by still hot volcanic ejections. Now, we have already seen that the temperature of the water in the tube increases rapidly with the depth, but is, at every depth to which observation extends, short of the boiling-point for that depth. Let absciss *a d* (Fig. 91) represent depth in the tube, and also pressures; and the corresponding temperature be measured on the ordinate *a n*. If, then, *a b*, *b c*, *c d*, represent equal depths of thirty-three or more feet, which is equal to one atmospheric pressure, the curve *e f* passing through 212°, 250°, 275°, and 293°, at the horizontal lines, representing one atmosphere, two atmospheres, three atmospheres, etc., would correctly represent the increasing boiling-points as we pass downward. We shall call this line, *e f*, *the curve of boiling-point.* The line *a g* commencing at the surface at 180°, and gradually approaching the boiling-point line, but everywhere within it, would represent the actual temperature in a state of quiescence. We shall call this *the line of actual temperature.* Now, Bunsen found that, as the time of eruption approached, the temperature at every depth approached the boiling-point for that depth—i. e., the line *a g* moved toward the line *e f.* There is no doubt, therefore, that, at the moment of eruption, at some point below the reach of observation, the line *a g* actually touches the line *e f*—the boiling-point for that depth is actually reached. As soon as this occurs, a quantity of water in the lower portion of the tube, or perhaps even in the subterranean channels which lead to the tube, would be changed into steam, and the expanding steam would lift the whole column of water in the tube, and cause the water in the basin to *bulge and overflow.* As soon as the water overflowed, the pressure would be diminished in every part of the tube, and consequently a large quantity of water before very near the boiling-point would flash into steam and instantly eject the whole of the water in the pipe; and the steam itself would rush out immediately afterward. The premonitory cannonading beneath is evidently produced by the collapse of large steam-bubbles rising through the cooler water of the upper part of the tube; in other words, it is *simmering on a huge scale.* An eruption is more quickly brought on by throwing stones into the throat of the geyser, because the circulation is thus more effectually impeded.

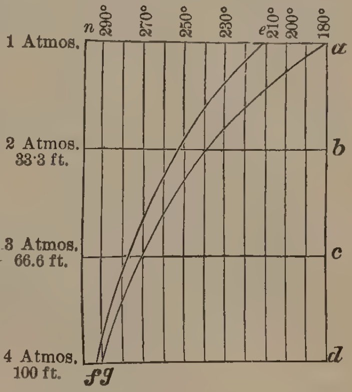

FIG. 91.

The theory given above is substantially that of Bunsen for the eruption of the Great Geyser, but modified to make it applicable to all geysers. In the Great Geyser, as already stated, Bunsen found a point forty-five feet deep, where the temperature was nearer the boiling-point than at any *within* reach of observation. This point, forty-five feet deep, plays an important part in Bunsen's theory. To illustrate: if *e f* (Fig. 93) represent again the curve of boiling-point, then the curve of actual temperature in the Great Geyser tube would be the irregular line *a g h*. At the moment of eruption, this line touched boiling-point at *g*. Then would follow the instantaneous formation of steam, and the phenomena of an eruption. But it is extremely unlikely that this condition should exist in all geysers; neither is it all necessary in order to explain the phenomenon of an eruption.

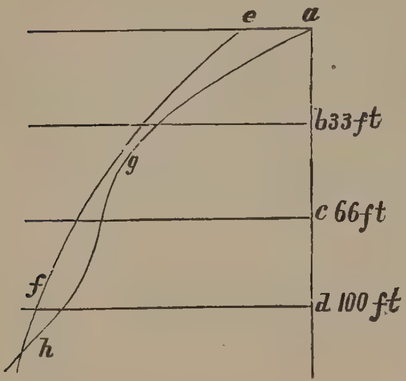

Fig. 92.

To prove beyond question the truth of this theory, Bunsen constructed an artificial geyser. The apparatus (Fig. 93) consisted of a tube of tinned sheet-iron about ten feet long, expanding into a dish above for catching the erupted water. It may or may not be expanded below for the convenience of heating. It was heated, also, a little below the middle, by an encircling charcoal chauffer, to represent the point of nearest approach to the boiling-point in the geyser-tube. When this apparatus was heated at the two points, as shown in the figure, the phenomena of geyser-eruption were completely reproduced: first, the violent explosive simmering, then the overflow, then the eruption, and then the state of quiescence. In Bunsen's experiment, the eruptions occurred about every thirty minutes.

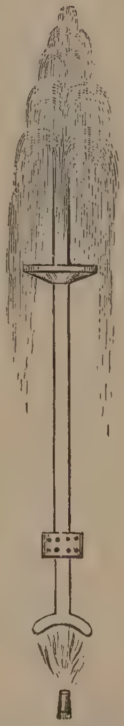

Fig. 93.—Artificial Geyser.

Bunsen's Theory of Geyser-Formation.—According to Bunsen, a geyser does not find a cave, or even a perpendicular tube, ready made, but, like volcanoes, makes its own tube. Fig. 94 is an ideal section of a geyser-mound, showing the manner in which, according to this view, it is formed. The irregular line, *b a c*, is the original surface, and *a* the position of a hot spring. If the spring be not alkaline, it will remain an ordinary hot spring; but, if it be alkaline, it will hold silica in solution, and the silica will be deposited about the spring. Thus the mound and tube are gradually built up. For a long time the spring will not be eruptive, for the circulation will maintain a nearly equal temperature in every part of the tube—it may be a *boiling*, but not an eruptive spring. But, as the tube becomes longer, and the circulation more and more impeded, the difference of temperature between the upper and lower parts of the tube becomes greater and greater, until, finally, the boiling-point is reached below, while the water above is comparatively cool. Then the eruption commences. Finally, from the gradual failure of the subterranean heat, or from the increasing length of the tube repressing the formation of steam, the eruptions gradually cease. Bunsen found geysers in different stages of development—some playful springs without tubes; some with short tubes, not yet eruptive; some with long tubes, violently eruptive; some becoming old and indisposed to erupt unless angered by throwing stones down the throat.

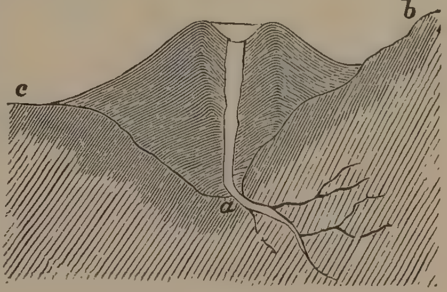

FIG. 94.—Ideal Section of a Geyser-Tube, according to Bunsen.

It is evident, however, that Bunsen's theory of geyser-eruption is independent of his theory of geyser-formation. A tube or fissure of any kind, and formed in any way, if long enough, would give rise to the same phenomena. The Yellowstone geysers have mounds or chimney-like cones, but it is by no means certain that the whole length of their eruptive tubes has been built up by siliceous deposit. Bunsen's theory of eruption none the less, however, applies to these also.

SECTION 3.—EARTHQUAKES.

Only recently, and mainly through the labors of Mr. Mallet,* of England, our knowledge on the subject of earthquakes has commenced to take on scientific form. This slowness of advance has arisen not from any want of materials, but from the great complexity of the phenomena, their origin deep within the bowels of the earth, and therefore removed from observation, and, more than all, from the surprise and alarm usually produced unfitting the mind for scientific observation. For these reasons, until thirty or forty years ago, the state of knowledge on this subject was much the same as it was 2,000 years ago. And yet now, we think, our knowledge of earthquakes is even more advanced than that of volcanoes.

Frequency.—Mallet, in his earthquake catalogue, has collected the records of 6,830 earthquakes as occurring in 3,456 years previous to 1850; but, of that number, 3,240, or nearly one half, occurred in the last fifty years; not because earthquakes were more numerous, but because the records were more perfect. According to the more complete catalogue of Alexis Perrey,* from 1843 to 1872, inclusive, there were 17,249, or 575 per annum. In Japan alone there are, on an average, two shocks per day.† Its seems probable, therefore, that, considering the fact that even now the larger number of earthquakes are not recorded, occurring in mid-ocean or in uncivilized regions, the earth is *constantly quaking* in some portion of its surface.

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* Transactions of British Association, 1850–1858; also, Principles of Seismology.

Connection with other Forms of Igneous Agency.—The close connection of earthquakes with volcanoes is undoubted: 1. Volcanic eruptions, especially those of the explosive type, are always preceded and accompanied by earthquakes. 2. Earthquake-shocks which have continued to trouble a particular region for a long time, often suddenly cease when an outburst takes place in a neighboring volcano, showing that the latter are safety-vents for the interior forces which produce earthquakes. Also, the sudden cessation of accustomed volcanic activity will often bring on earthquakes. Thus, when the wreath of smoke disappears from Cotopaxi, the inhabitants of Quito expect earthquakes. During the great Calabrian earthquakes of 1783, Stromboli, for the first time in the memory of man, ceased erupting. The great earthquake which destroyed Riobamba in 1797, and in which 40,000 persons perished, took place immediately after the stopping of activity in a neighboring volcano. The earthquake-shocks which destroyed Carácas in 1812 ceased as soon as St. Vincent, 500 miles distant, commenced erupting. 3. Examination of Prof. Mallet's earthquake-map shows that the distribution of earthquake-centers is much the same as that of volcanoes already given (page 90). It may be regarded as almost certain, therefore, that the forces which generate earthquakes are closely allied, if not identical, with those which produce volcanic eruptions.

Again, the connection of earthquakes with bodily movements of great areas of the earth's crust, by elevation or depression, is equally close. In 1835, after a great earthquake, which shook the coast of South America over an area of 600,000 square miles, the whole coast-line of Chili and Patagonia was found elevated from two to ten feet above sea-level. Again, in 1822, after a similar earthquake in the same region, the coast-line was found elevated from two to seven feet. Now, in this very region, old beach-marks, 100 feet to 1,300 feet above the sea-level, and extending 1,200 miles along the coast on each side of the southern end of this continent, plainly show that, in very recent geological times, the whole southern end of South America has been bodily raised out of the sea to that extent. It is impossible to doubt that the force which produced this continental elevation was also the cause of the accompanying earthquakes. Again, in 1819, after a severe earthquake, which shook the whole region about the mouth of the Indus, a large tract of land of 2,000 square miles was sunk and became a salt lagoon; while another area, fifty miles long and ten to sixteen miles wide, was elevated ten feet. In commemoration of this wonderful event, the raised portion was called Ullah Bund, or the Mound of God. Again, in 1811, a severe earthquake shook the valley of the Mississippi. In the region about the mouth of the Ohio, where it was severest, large tracts of land were sunk bodily several feet below their former level, and have been covered with water ever since. It is now called the "*Sunk Country.*" The Inyo earthquake of 1872 was accompanied by a fissure of forty miles in length and a slip or fault of twenty-five feet.* In the Sonora earthquake of 1887 there was a fissure for a hundred miles and a vertical slip of eight feet.† In the Japan earthquake of 1891, there was a fissure seventy miles long and a slip of twenty feet.‡ We might multiply examples if necessary. Nearly all earthquakes, if carefully studied, have shown such fissures and slips. Fissures and faults, formed in previous geological times, are found intersecting the earth in all directions. We see them, in these cases, formed under our eyes, and in connection with earthquakes.

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* American Journal of Science, vol. xi, p. 233, 1876.

† Transactions of the Seismological Society of Japan, vol. vi, Part II, p. 79. Nature, vol. xl, p. 657, 1889. Later observations make it three to four per day (Milne).

Ultimate Cause of Earthquakes.—The connection of earthquakes with the two other forms of igneous agency suggests each a possible cause. Preceding and accompanying volcanic eruptions, especially of the explosive type, occur subterranean explosions, which are often heard hundreds of miles. Such eruptions are also accompanied with escape of immense quantities of steam and gas. These facts, together with the association of earthquakes with volcanoes, have suggested the idea that the sudden formation or the sudden collapse of vapor is the cause of earthquakes. According to this view, an earthquake is, on a grand scale, a phenomenon similar to the *jar* produced by the explosion of a keg of gunpowder buried in the earth.

But the association of earthquakes with bodily movements of the earth's crust over large areas, suggests another and far more probable cause. It is well known that there are operating, in the interior of the earth, forces tending to elevate or depress or to crush together laterally the earth's crust. We shall discuss the nature of these forces hereafter. Suffice it to say now that in this way mountain-ranges are formed and continents elevated. One effect of these forces is to break the earth's crust into great blocks many miles in length and breadth and several miles in thickness. These blocks do not remain in their original position, but are always slipped one on another, producing displacement often thousands of feet. Such great crust-blocks separated by profound fissures, and slipped one on another, are found everywhere. They are, in fact, among the commonest of geological occurrences. They will be described in Part II. Some of these fissures are doubtless *now* forming; many of them are *still slipping.* Suppose, then, a subterranean force, tending to elevate a portion of the earth's crust, and gradually increasing but resisted by the rigidity of the crust. It is evident that the time would finally come when the crust would break, by a fracture extending perhaps hundreds of miles in length and through several miles in depth of solid rock. Such a fracture would certainly cause an earth-jar great enough to produce all the dreadful effects of an earthquake. But, again, the enormous crust-blocks thus formed would inevitably from time to time *settle*, or readjust themselves to new positions. Every such readjustment would also produce an earthquake. We conclude, therefore, that *by far the most common cause of earthquakes is either the formation of a great fissure or else the readjustment of the walls of such a fissure.* Even in the case of the tremors accompanying volcanic eruptions, it is probable that their true cause is the fracturing of the mountain by the eruptive forces and the readjustment of the broken parts.

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* Gilbert, Nat., vol. xxix, p. 45, 1883.

† Science, vol. x, p. 81, 1887.

‡ Koto, Geological Mag., vol. i, p. 144, 1894.

Proximate Cause.—But whatever be our view of the ultimate cause of earthquakes, there can be no doubt that the *proximate* or immediate cause of the observed effects is the arrival of an earth-jar—the emergence, on the earth-surface, of a succession of elastic earth-waves, produced by a violent concussion of some kind in the interior. Evidently, therefore, the discussion of earthquake-phenomena is nothing more than the discussion of the laws of propagation and the effects of elastic earth-waves occurring under peculiar and very complex conditions.

Application to Earthquakes.—Suppose, then, a concussion of any kind to occur at a considerable depth (x, Fig. 95), say ten or twenty miles, beneath the earth-surface, S S. Taking, for simplicity sake, the origin as a point, a series of elastic spherical waves, similar to *sound-waves*, will be generated, consisting of alternate compressed and rarefied shells, the whole expanding with great rapidity in all directions until they reach the surface at a. From this point of first emergence immediately above the focus x, the still-enlarging spherical shells would outcrop in rapidly-expanding *circular waves*, $b'' b''$, $c'' c''$, $d'' d''$ (Fig. 95), similar in form to water-waves, but very different in character. This we will call the *surface-wave.* The circles here drawn would equally represent a series of waves, or the same wave in successive degrees of enlargement.

This *surface-wave* would not be a normal wave propagating itself like a water-wave. It would be only the outcropping or emergence of the ever-widening spherical wave on the earth-surface. Both its velocity of transit along the surface, and the direction of its vibration in relation to the surface, will vary continually according to a simple law. The *direction of vibration*, being along the radii $x\ a$, $x\ b$, $x\ c$, etc., will be perpendicular to the surface at a, and become more inclined until it finally becomes parallel with the surface at an infinite distance. The *velocity of its transit* will be infinite at a, and then gradually decrease until, if we regard the surface as a plane surface, at an infinite distance it reaches its limit, which is the volocity of the spherical wave. Between these two extremes of infinity at a, and the velocity of the spherical wave at infinite distance, the velocity of the surface-wave varies inversely as the cosine, or directly as the secant, of the angle of emergence $x\ b\ a$, $x\ c\ a$, etc.

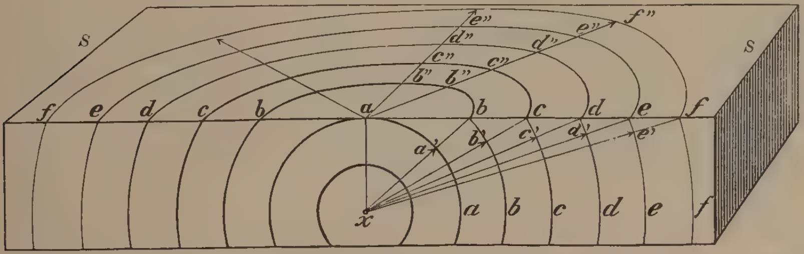

FIG. 95.—Section and Perspective View of a Portion of the Earth's Crust shaken by an Earthquake, showing the origin, x, sections of the spherical waves, a, b, c, d, etc., and perspective of surface-wave, b'', c'', d'', etc.

For, if $a\ a$, $b\ b$, $c\ c$, $d\ d$, etc. (Fig. 95), be successive positions of the spherical wave, then the radii $x\ a$, $x\ b$, $x\ c$, would be the direction both of propagation and of vibration. Now, when the wave-front is at b, while the spherical wave moves from b' to c, the surface-wave would move from b to c; when the spherical wave moves from c' to d, the surface-wave moves from c to d, etc. If, therefore, $b\ c$, $c\ d$, etc., be taken very small, so that $b\ b'\ c$, $c\ c'\ d$, may be considered right-angled triangles, then in every position the surface-wave moves along the hypotenuse, while the spherical wave moves along the base of the small triangles $b\ b'\ c$, $c\ c'\ d$, etc. Letting $v =$ velocity of the spherical wave, and v' that of the surface-wave, and E the angle of emergence ($x\ b\ a$, $x\ c\ a$, etc., Fig. 95), we have the proportion—$v : v' :: 1 : sec.\ E$, and $v' = v.\ sec.\ E$, or if v is constant $v' \propto sec.\ E$. Therefore, at a, the point of first emergence, E being a right angle and $sec.\ E =$ infinity, $v' =$infinity. At an infinite distance from a the angle E becomes 0, and the secant $= 1$, and $v' = v.\ 1 = v$. That is, at the point of first emergence the velocity of the surface-wave is infinite; from this point it decreases as the secant of the angle of emergence decreases, until finally at an infinite distance it becomes equal to the velocity of the spherical wave.

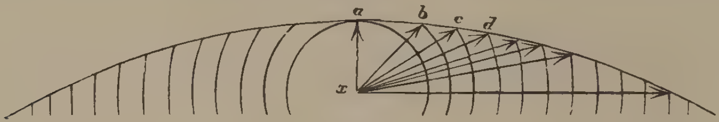

FIG. 96.

On a spherical surface (Fig. 96) it is evident that E never becomes 0, and therefore v' never reaches the limit v. If we conceived the wave to pass through the whole earth (Fig. 97), then the velocity of the surface-wave would decrease to a certain point where E is a minimum, say about c, and then would again increase to infinity on the other side of the earth, p, where E becomes again a right angle. If x be near the surface, v' would become nearly equal to v at some point of its course; but as x approaches the center, C, the limit of v' would be greater and greater, until, if x is at the center, v' would become infinite everywhere; i. e., a shock at the center would reach the surface everywhere at the same moment. We are indebted to Hopkins for this discussion of the relation of the velocity of the surface-wave to that of the spherical wave. It may therefore be called *Hopkins law.*

We have thus far taken the earth as homogeneous and of equal elasticity at all depths. But the earth certainly increases in density (p. 87), and therefore in elasticity as we approach the center. This fact would seriously affect the form of the earth-wave and, in a remarkable way, the velocity of its outcrop on the surface—i. e., the surface-wave. This has been worked out in a masterly way by Schmidt.* If, as before, $s\ s$ (Fig. 98), represent the surface of the earth and x the centrum of the earthquake, then the earth-wave would come from x to the epicentrum, a, without deviation, but with decreasing velocity, as shown by the decreasing spaces between the co-seismals. In all other directions, however, the waves would be refracted by passing from a denser to a rarer medium. The form of the wave, therefore, would not be perfectly spherical, but ellipsoidal, with the

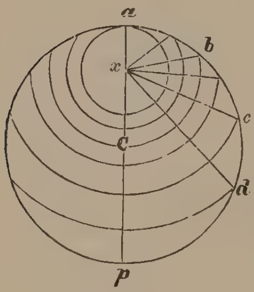

FIG. 97.

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* Nature, vol. ii, p. 631, 1895.

centrum in one focus of the ellipsoid. The radii—always normal to the wave-front —would be curved, with the concavity upward. Under these conditions it is evident that, as before, the velocity of the surface-wave would be infinite at the epicentrum, *a*, then decrease as before, but by a different law and more rapidly, would reach a minimum which would be equal to the velocity at the centrum, and thenceforward again increase to infinity at infinite distance. This is shown by the gradual approach of the radii to a position normal to the earth-surface. This may be called "*Schmidt's law.*" It undoubtedly explains many otherwise inexplicable phenomena of varying velocity of earthquake-waves as will be shown in the proper place.

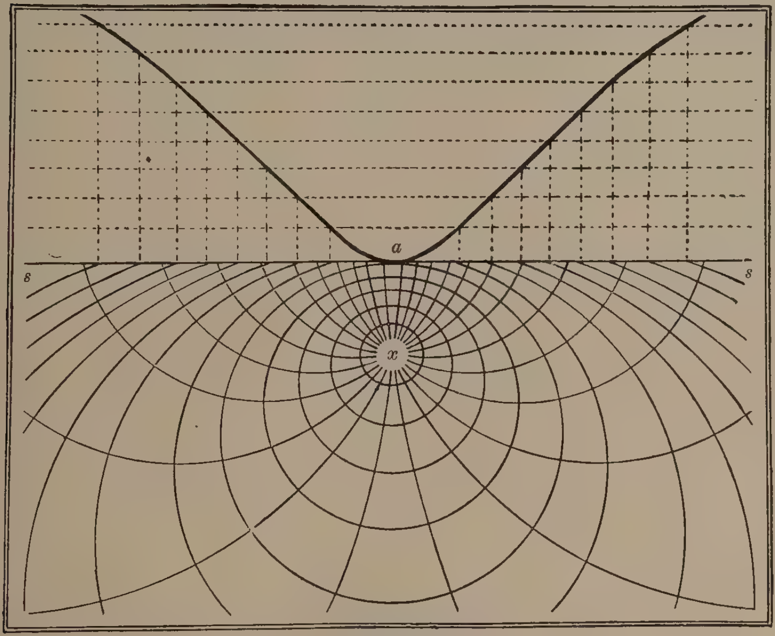

Fig. 98.—Diagram illustrating Schmidt's Law.

Experimental Determination of the Velocity of the Spherical Wave. —On the supposition that earthquakes are really produced by the emergence on the surface of a series of elastic earth-waves, Mallet undertook to determine experimentally the velocity of such waves. Two stations were taken about a mile or more apart, and connected by telegraphic apparatus; a keg of gunpowder was buried at one, and at the other was placed an observatory, in which was a clock, a mercury mirror, and a light, the image of which reflected from the mercury mirror, was thrown on a screen. The slightest tremor communicated to the mercury surface of course caused the image to dance. The moment of explosion was telegraphed; the moment of arrival of the earth-tremor was observed. The difference gave the *time* of transit; the distance, divided by the time, gave the velocity per second. In this manner Mallet found the velocity in sand 825 feet per second, or nearly nine and one half miles per minute; in slate 1,225 feet per second, or fourteen miles per minute; and in granite 1,665 feet per second, or nineteen miles per minute. As an earthquake-focus is always several miles beneath the surface, and as rocks at that depth are probably as hard as granite, nineteen miles per minute may be taken as the average velocity of earth-waves as determined by these experiments. It agrees well with the observed velocity of many earthquakes.*

This result was unexpected, considering the law that all elastic waves in the same medium run with the same velocity, for the velocity of sound in granite or slate is probably not less than 10,000 or 12,000 feet per second. The explanation is to be found in the very imperfect coherence and elasticity of rocks. The medium is broken by the passage of large and high waves of the explosion, but carries successfully the small waves of sound.

More recent experiments have given much higher velocities. In a series of very careful experiments Fouqué found in *sand* a velocity of 984 feet, in *carboniferous sandstone* about 7,400 feet, and in *granite* about 9,200 feet per second.† The explosion at Hallett's Point gave 5,000 to 8,000 feet per second, and that of Flood Rock, 4,500 to 20,000 feet per second (Abbot). These agree well with the observed velocity of some earthquakes. It should be remembered that all these experiments give only the velocity of the spherical wave, because on account of the very small depth of the focus the velocity of the spherical and surface waves are practically identical.

Character of the Earth-Wave.—For the sake of simplicity we have thus far spoken of the earth-wave as a simple spherical wave of longitudinal vibration like a sound-wave, but the seismograph shows that there are *transverse* as well as longitudinal vibrations. Thus, the earth-movement is very complex and produced by the superposition of several waves of different kinds. But the wave which we have been discussing is the dominant one and the one whose origin is most easily understood, and may therefore be called the *normal* wave. Fig. 99 is a wire model representing the actual motion of a point during an earthquake. It was made by combining the records of the three pendulums of Ewing's seismograph (Fig. 109).

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* Mallet, Second Report, Transactions of the British Association, 1851.

† Revue Scientifique, vol. xli, pp. 97, 161, 1888.

Explanation of Earthquake-Phenomena.—Earthquakes have been divided into three kinds, viz., the *explosive*, the *horizontally progressive*, and the *vorticose*. The first kind is described by Humboldt as a violent motion directly upward, by which the earth-crust is broken up, and bodies on the surface are thrown high in the air. The shock is extremely violent, but does not extend very far. In the second, the shock spreads on the surface like the waves on water to a great distance. In the third there is a whirling motion of the earth entirely different from ordinary wave-motion. These three kinds are sometimes supposed to be essentially distinct, and possibly produced by different causes: but we will attempt to show that the difference is wholly due to the different conditions under which the waves emerge on the surface. The three kinds are, in fact, often united in the same earthquake.

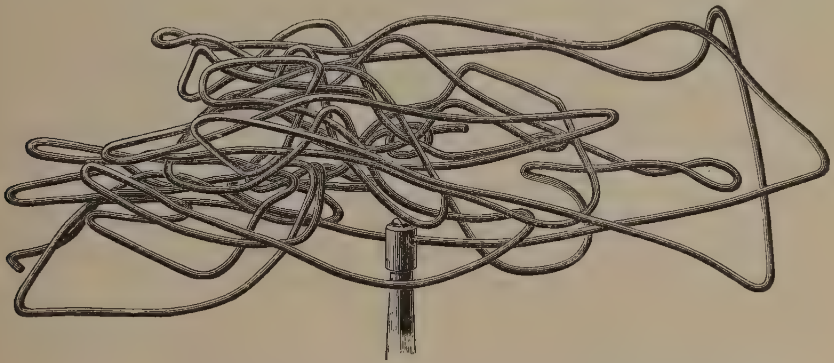

FIG. 99.—Model showing the Path of a Particle during an Earthquake (after Sekiya).

The most remarkable example of explosive earthquake is that which destroyed Riobamba in 1797. In this dreadful earthquake the shock came suddenly, like the explosion of a mine. Not only was the earth broken up and rent in various places, but objects lying on the surface of the earth were thrown violently upward; bodies of men were hurled several hundred feet in the air, and afterward were found across a river and on the top of a hill. In earthquakes of this kind —1. The impulse is very powerful and sudden, so as to make a high but not a long wave, or, in other words, the velocity of vibration or of the shock is very great; and, 2. The focus is not deep, so that the velocity of the shock-motion does not become small before it reaches the surface. At Riobamba the velocity of the shock-motion was still very great when the wave reached the surface. From the distance bodies were thrown, Mallet supposes the velocity of the shock-motion could not have been less than eighty feet per second (Jukes).

The *horizontally progressive kind* may be regarded as the true type of an earthquake; it is in fact the spreading surface-wave already explained. If the elasticity of the earth, and therefore the velocity of the waves, is the same in all directions, the surface-wave will spread in concentric *circles;* but if the elasticity, and therefore the velocity of the waves, be greater in one direction than in another, as, for example, north and south than east and west, or the converse, then the form of the outcrop will be *elliptical.* In some rare cases the shock seems to run along a line. Thus progressive earthquakes have been subdivided into *circular*, *elliptical*, and *linear* progressive. We have already given the simple explanation of the first two; the last may be briefly explained as follows:

Let it be borne in mind: 1. That these linear earthquakes usually run along mountain-chains; 2. That most great mountain-chains consist of a granite axis (appearing along the crest and evidently connected beneath with the great interior rocky mass of the earth), flanked on each side with stratified rocks consisting of many different kinds; 3. When elastic waves pass from one medium to another of different elasticity, in all cases a part of the wave passes through, but a part is always *reflected.* For every such change—for every layer—a reflection occurs; and, therefore, if there are many such layers, the waves are quickly quenched. If, now, Fig. 100 represent a transverse section across such a mountain, and X the focus of an earthquake, it is evident that the portion of the enlarging spherical wave which emerged along the axis a would reach the surface successfully; while those portions which struck against the strata of the flanks would be partially or wholly quenched. The mode of outcrop on the surface is shown in the map-view, Fig. 101, in which a is the epicentrum, b b the granite axis, and c c the stratified flanks. It must be remembered also that the origin of most earthquakes is by the formation or the readjustment of a fissure. In such a case the shock will be simultaneous and severe all along the fissure. It is probable that many so-called linear earthquakes are thus accounted for.

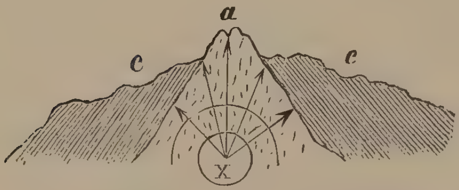

FIG. 100.—Diagram illustrating Linear Earthquakes.

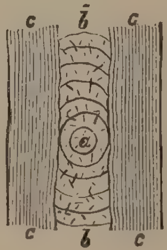

FIG. 101.

The velocity of the surface-waves, as observed in some severe earthquakes, is about twenty miles per minute. This accords well with Mallet's experiments in granite. In some earthquakes the velocity has been found to be twelve to fifteen miles (Mallet's results in slate), and in some as high as thirty to thirty-five miles per minute. In the Charleston earthquake of August, 1886, the velocity of one hundred to one hundred and twenty miles per minute was observed. This agrees with the result of Fouqué in granite. In some *slight* shocks, the velocity, as determined by telegraph, is estimated as high as one hundred and forty miles per minute, or 12,000 feet per second.

This amazing difference is doubtless partly due to inaccuracy of observation, but it may also be partly explained thus: It will be remembered that by Hopkins's law the velocity of the surface-wave is infinite at the epicentrum, and diminishes, according to a law already discussed, until it reaches, or nearly reaches, the velocity of the spherical wave. Now, if the earthquake-focus be comparatively shallow, the initial velocity of the surface-wave very rapidly approaches its minimum, and therefore the observed velocity of the surface-wave may be taken as nearly the same as that of the spherical wave; but, if the earthquake be very deep, the diminution, even on a *plane* surface, is far less rapid; and when we take into consideration the curvature of the earth-surface, it is evident that the velocity of the surface-wave may be for all distances much greater than that of the spherical wave. This would well account for velocities of thirty to thirty-five miles, but not for velocities of one hundred or one hundred and forty miles. This latter is accounted for by another principle.

These very high velocities occur mostly in slight shocks. Now, while heavy shocks (large and high waves) break the medium at every step of their passage, and are therefore retarded, as already explained, slight tremors (small and low waves) are successfully transmitted without rupture, and therefore run with the natural velocity belonging to the medium, i. e., the velocity of sound. Now, the velocity of sound in granite is probably about 12,000 feet per second, or one hundred and forty miles per minute. In the Charleston earthquake, however, though a severe one, the waves seem to have been transmitted with nearly the normal velocity belonging to the medium. The more recent and accurate determinations of Prof. Milne make the average velocity of an earthquake wave about two miles per second and of tremors about three miles per second.*

Finally, to all these causes of high velocity must be added Schmidt's principle of rapid decrease of the velocity of the surface-wave to a minimum and then increase again to infinity. This accounts for the high velocity of slight tremors; for these occur at great distance from the epicentrum.

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* Rep. to Brit. Assoc., 1895.

Vorticose Earthquakes.—In these cases the ground is twisted or whirled round and back, or sometimes ruptured and left in a twisted condition. The most conspicuous examples of this kind of motion occurred in the earthquake of Riobamba and in the great Calabrian earthquake of 1783. In this latter earthquake the *blocks of stone forming obelisks were twisted one on another*; the earth was broken and twisted, so that *straight rows of trees were left in interrupted zigzags.* Phenomena similar to some of these were observed also in the California earthquake of 1868. Chimney-tops were separated at their junction with roofs, and twisted around without overthrow; wardrobes and bureaus turned about at right angles to the wall, or even with their faces to the wall.

Explanation.—Some of these effects—such as twisting of obelisks and chimney-tops, and turning about of bureaus, etc.—may be explained, as Lyell has shown, without any twisting motion of the earth at all, or any other than the backward-and-forward motion common to all earthquakes. Thus, if we place one brick on another, and shake them back and forth, holding only the lower one, they are almost certain to be left twisted one on the other. The reason is, that the adhesion is almost certain to be greater toward one end than the other —the center of friction does not coincide with the center of gravity. This is the probable explanation of twisted obelisks and chimney-tops, etc. Also, the simple back-and-forth shaking of a wardrobe in a diagonal direction, would almost certainly lift up one end and swing it around. The vorticose motion in such cases is probably not real, but *only apparent.*

But there are other cases of undoubtedly *real* vorticose motion; as, for example, straight rows of trees changed into interrupted zigzags by fissures and displacement. All such cases of *real twisting* are probably explicable on the principle of *concurrence and interference of waves.* If two systems of waves of any kind meet each other, there will be points of concurrence where they *re-enforce each other*, and points of interference where they *destroy each other.* Suppose, for instance, a system of water-waves, represented by the double lines *i*, *i* (Fig. 102), running in the direction *b b*, strike against a wall, *w w*: the waves would be reflected in the direction *c c*, and are represented by the single lines *r*, *r*. Then, if the lines represent crests, and the intervening space the troughs, at the places marked with crosses and dots there would be concurrence, and therefore higher crests and deeper troughs, while at the points indicated by a dash there would be interference and mutual destruction, and therefore smooth water. The same takes place in earth-waves. If two systems of earth-waves meet and cross each other, we must have points of concurrence and interference in close proximity. The ground, therefore, will be thrown into violent agitation—points in close proximity moving in opposite directions (twisting). If the motion be sufficient to rupture the earth, restoration is not made by *counter-twisting*, and the earth is left in a displaced condition.

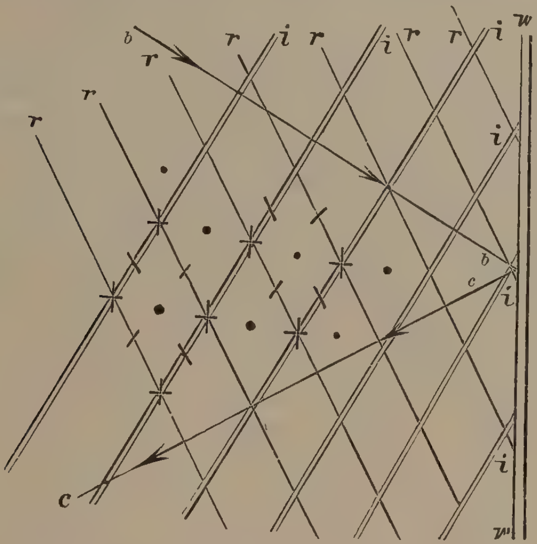

Fig. 102.—Diagram illustrating Reflection of Waves—Map View.

The causes of interference may be various—sometimes by the normal and transverse waves combining differently so as to produce motion in different directions in contiguous places; sometimes by difference of velocity of waves, already explained, by which some overrun others, concurring and interfering; more often it is the result of reflection from surfaces of different elasticity. For example, it is well known that the most violent effects of earthquakes, especially twisting of the ground, usually occur near the junction of the softer strata of the plains with the harder and more elastic strata of the mountains. Now, suppose from a shock at *X* (Fig. 103) a system of earth-waves should emerge at *a*, and run as a surface-wave toward the mountain *m*. The

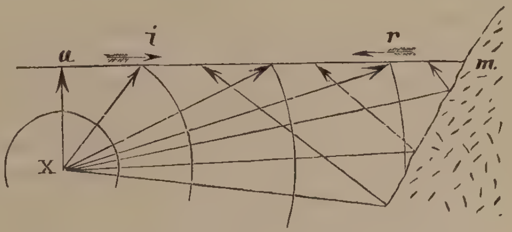

Fig. 103.—Reflection of Earthquake-Waves—Section.

waves, striking the hard, elastic material *m*, would be partly transmitted and partly reflected. The reflected waves running in the direction of the arrow *r*, would meet the advancing incident waves moving in the direction of the arrow *i*, and concurrence and interference would be inevitable.*

Minor Phenomena.—Not only the several kinds of earthquakes, but many of the minor phenomena are explained by the wave-theory.

1. *Sounds.*—These are usually described as a *hollow rumbling*, *rolling*, or *grinding*; sometimes as clashing, thundering, or cannonading. They are probably produced by rupture of the earth at the *origin*, and by the passage of the wave through the imperfectly elastic rocky medium *breaking the medium and grinding the broken parts together.* But what is especially noteworthy is, that these sounds *precede* as well as accompany the shocks. In every earthquake there are transmitted waves of every variety of size. The great waves are sensible as shocks, or jars, or tremors; the very small waves, too small to be appreciated as tremors, are heard as sounds. But, as already explained, these last run with greater velocity in an imperfectly coherent medium like the earth, and therefore arrive sooner than the great waves, which constitute the shock. The same was observed in Mallet's experiments.

2. *Motion.*—As to *direction*, the observed motion is sometimes vertically *up and down*, sometimes horizontally *back and forth*, and sometimes *oblique* to the horizon. Almost always a *rocking motion*, i. e., a leaning of tall objects first in one direction and then in the other, is observed. As to *violence* or velocity of motion, this is sometimes so great that objects are thrown into the air, and whole cities are shaken down as if they were a mere collection of card-houses; while in other cases only a slow swinging, or heaving, or gentle rocking, is observed.

If we confine our attention to the principal or normal wave, the difference in *direction* is wholly due to the position of the observer. At the epicentrum it is of course *vertical*, and thence it becomes more and more oblique, until at great distances it is usually *horizontal.* The *violence* of the shock or *velocity* of ground-motion depends partly upon the violence of the original concussion, and partly on the distance from the origin or *focus.* This velocity of the ground-motion must not be confounded with the velocity of the wave already discussed. The latter is the velocity of *transit* from place to place; the former is the velocity of *oscillation* up and down, or back and forth. The velocity of oscillation has no relation to the velocity of transit, but depends only on the height of the wave, which constantly diminishes and becomes finally very small, though the velocity of transit remains the same, and always enormously great. The *rocking-motion* is also easily explained. A series of waves, somewhat similar in form to water-waves (though differing in nature), actually passes beneath the observer. Of course, when an object is on the *front-slope*, it will lean in the direction of transit; and when on the *hind-slope*, in the contrary direction.

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* For an excellent discussion of the effects of interference of earth-waves, see a memoir by Prof. John Milne, Transactions of the Seismological Society of Japan, vol. i, Part II, p. 82.

3. *Circle of Principal Destruction.*—In some earthquakes a certain zone at considerable distance from the point of first emergence (epicentrum) has been observed, within which the destruction by overthrow is very great, and beyond which it speedily diminishes. This has been called the circle of principal destruction or overthrow. It is thus explained: The overthrow of buildings depends not so much on the *amount* of oscillation as upon the horizontal element of the oscillation. Now, the whole amount of oscillation is greatest at the point of first emergence, and decreases outward; but the horizontal element is nothing at a, and increases as the cosine of the angle of emergence. Therefore, under the influence of these two conditions, one decreasing the whole oscillation, the other increasing the horizontal element of that oscillation, it is evident that there will be a point on every side, or, in other words, a circle, where the horizontal element will be a maximum. This is shown in Fig. 104, in which $a\,a'$, $b\,b'$, $c\,c'$, etc., are the decreasing oscillation, and $b\,b''$, $c\,c''$, are the horizontal element. This reaches a maximum at c. It has been found by mathematical calculation, based upon the supposition that the whole oscillation varies inversely as the square of the distance from X, that the horizontal element will be a maximum when the angle of emergence is 54° 44′. By determining by observation the circle of principal disturbance, it is easy to calculate the depth $a\,X$ of the focus, for it will be the apex of a cone whose base is that circle, and whose apical angle is 70° 32′.*

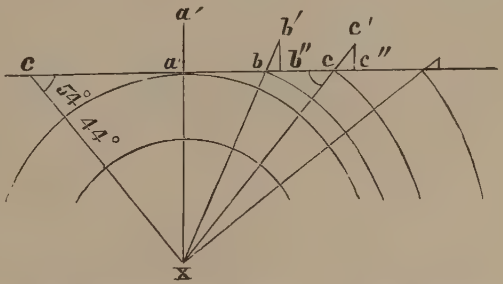

FIG. 104.—Diagram illustrating Circle of Principal Disturbance.

4. *Shocks more severely felt in Mines.*—It has been sometimes observed that shocks are distinctly felt in mines which are insensible at

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* Mallet's Report for 1858, p. 101.

the surface. This is probably explained as follows: Let *S S* (Fig. 105) be the surface of the ground: and let *a b* represent hard, elastic strata, covered with loose, inelastic materials, *c c*. Now, if a series of waves come in the direction of the arrows *d d*, and, passing through *a b* on their way to the surface, strike upon the lower surface of *c c*, a portion would reach the surface by refraction, but a portion would be reflected and return into *a b*, concurring and interfering with the advancing waves, and producing great commotion in these strata.

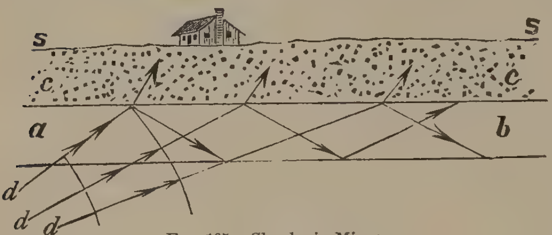

Fig. 105.—Shocks in Mines.

5. *Shocks less severe in Mines.*—This case is probably more common than the last. It was notably the case in the earthquake of 1872 in Inyo County, California. While the surface was severely shaken, many houses destroyed, and large fissures formed in the earth, the miners, several hundred feet below the surface in the hard rock, scarcely felt it at all. This is probably, at least partly, explained as follows: As long as the wave travels within the earth, motion of the particles is restrained by the work of elastic compression; but, as soon as the surface is reached, the motion becomes free, and the velocity of shock is far greater than before, often so great as to throw bodies high in the air. The phenomenon is exactly like that in the familiar experiment of the ivory balls: when the first in the series is struck, an elastic wave of compression passes through all, but only the last one moves.

6. *Bridges.*—In a manner somewhat similar are to be accounted for the phenomena of bridges. In the earthquake regions of South America there are certain favored spots, often of small extent, which are partially exempt from the shocks which infest the surrounding country. The earthquake-wave seems to pass under them as under a bridge, to reappear again on the other side. The mere inspection of Fig. 106 will explain the probable cause of this exemption, viz.: reflection from the under surface of an isolated mass of soft, inelastic strata, *c c*.

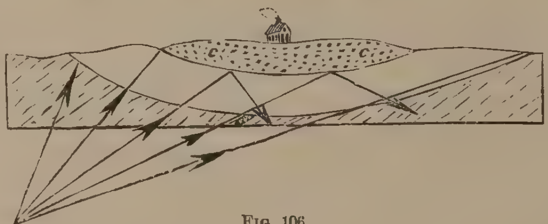

Fig. 106.

7. *Fissures.*—The ground-fissures, so commonly produced by earthquakes, are sometimes of the nature of the *great fissures* of the crust, which are the probable cause of earthquakes. Such great fissures are usually wholly beneath the surface at great depth, but sometimes may break through and appear on the surface. This is certainly the case when *decided faults* occur with elevation or depression of large tracts of land. But the surface-fissures so frequently described, small in size, very numerous, and running in all directions, have an entirely different origin. They are evidently produced by the shattering of the softer, more incoherent, and inelastic surface-soil, and by the passage of the earth-wave. Even the more elastic underlying rock is broken by the same cause, but to a much less extent.

Earthquakes originating beneath the Ocean.

We have thus far spoken of earthquakes originating beneath the land-surface. But three fourths of the earth-surface is covered by the sea; and we have already seen that other forms of igneous agency are most abundant in and about the sea. As we might expect, therefore, the greater number of earthquake-shocks (eighty-four per cent) occur beneath the sea-bed. It is worthy of remark that this is especially true of the *sea-bed immediately bordering the continents*, and still more especially if the slope of bottom is steep. In such, the phenomena already described are often complicated by the addition of the "*Great Sea-Wave.*"

Suppose, then, an earthquake-shock to occur beneath the sea-bed; the following waves will be formed: 1. As before, a series of elastic spherical waves will spread from the focus, until they emerge on the sea-bed. 2. As before, a series of circular surface-waves, the outcrop of the spherical waves, will spread on the sea-bottom until they reach the nearest shore, and perhaps produce destructive effects there. 3. On the back of this submarine earth-wave is carried a corresponding sea-wave. This is called the "*forced sea-wave*," since it is not a free wave, but a forced accompaniment of the ground-wave beneath. It reaches the shore at the same time as the earth-wave. It is of little importance. 4. In addition to all these is formed the *great sea-wave;* or *tidal wave*, as it is sometimes, but wrongly, called.

Great Sea-Wave.—This common and often very destructive accompaniment of earthquakes is formed as follows: The sudden upheaval of the sea-bed lifts the whole mass of superincumbent water to an equal extent, forming a huge mound. This movement of the sea-bed is not due to the mere emergence of the earth-wave, for this is far too small to produce such effects; but is due to *bodily movement of the earth-crust* by *displacement* of a fissure which, as we have seen, is the usual cause of earthquakes. The falling again of this water as far *below* as it was before *above* its natural level generates a *circular wave of gravity*, which spreads like other water-waves, maintaining its original wave-length, but gradually diminishing its wave-height until it becomes insensible. Usually, a *series* of such waves is formed. These waves are often 100 to 200 miles across their base (wave-length) and fifty to sixty feet high at their origin. Their destructive effects may be inferred from the enormous quantity of water they contain. In the open sea they create no current, and are not even perceived; but, when they touch bottom near shore, they pile up and rush forward as great breakers fifty or sixty feet high, sweeping away everything in their course.

Being waves of gravity, their velocity, though very great on account of their size, is far less than that of the earth-waves, and they reach the neighboring shore, therefore, some time later, and often complete the destruction commenced by the earth-waves.

Examples of the Sea-Wave.—In the great earthquake which destroyed Lisbon in 1755, the epicentrum was on the sea-bed fifty or more miles off the coast of Portugal. From this point the surface earth-waves spread along the sea-bottom until they reached shore. It was the arrival of these waves which destroyed Lisbon. About a half-hour later, when all had become quiet, several great sea-waves, one of them sixty feet high, came rushing in, deluging the whole coast and completing the destruction commenced by the earth-waves. This wave was thirty feet high at Cadiz, eighteen feet at Madeira, and five feet on the coast of Ireland. It was sensible on the coast of Norway, and even on the coast of the West Indies, after having crossed the whole breadth of the Atlantic.

In 1854 a great earthquake shook the coast of Japan. Its focus was evidently beneath the sea-bed some distance off the coast, for, in about a half-hour, a series of water-waves thirty feet high rushed upon shore and completely swept away the town of Simoda. From the same center the waves, of course, spread in the contrary direction, traversed the whole breadth of the Pacific, and in about twelve and a quarter hours struck on the coast of California at San Francisco, and swept down the coast to San Diego. These waves were thirty feet high at Simoda, fifteen feet high at Peel's Island, about 1,000 miles off the coast of Japan, 0·65 feet, or eight inches, high at San Francisco, and six inches at San Diego.*

On the 13th of August, 1868, a great earthquake desolated the coast of Peru. Its focus was evidently but a little way off shore, for in less than a half-hour a series of water-waves fifty or sixty feet high rushed in and greatly increased the devastation commenced by the earth-waves. These waves reached Coquimbo, 800 miles distant, in three hours; Honolulu, Sandwich Islands, 5,580 miles, in twelve hours; the Japan coast, over 10,000 miles, the next day. They were also observed on the coast of California, Oregon, and Alaska, over 6,000 miles in one direction, and on the Australian coast, nearly 8,000 miles in another direction. This series of waves was distinctly sensible at a distance of nearly half the circumference of the earth. Had it not been for the barrier of the South American Continent, it would have encircled the globe.*

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* Report of Coast Survey for 1862.

Many other earthquake sea-waves have been observed and recorded by tidal gauges, especially those of the Iquique earthquake of May, 1877, and the waves caused by the great eruption of Krakatoa, August, 1883. In Fig. 107 we give the record of the Iquique earthquake taken by the tidal gauge at San Francisco.

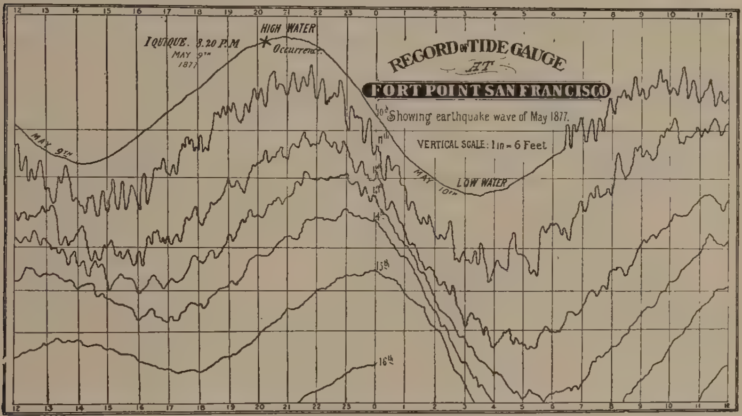

FIG. 107.—Record of Waves of the Iquique Earthquake (after Milne). The cross, ×, marks the time of occurrence at Iquique.

There are several points in the above description which we must very briefly explain:

1. The velocity of these great sea-waves, though less than that of the earth-waves, is still very great in comparison with ordinary sea-waves. The waves of the Japan earthquake crossed the Pacific to San Francisco, a distance of 4,525 miles, in a little more than twelve hours, and therefore at a rate of 370 miles per hour, or over six miles per minute. The waves of the South American earthquake of 1868 ran to the Hawaiian Islands at a rate of 454 miles per hour. This amazing velocity is the result of the great *size of these waves;* for the velocity of water-waves varies as the square root of the wave-length ($v \propto \sqrt{L}$).

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* Report of Coast Survey for 1869.

2. The *size* of these great waves is determined by multiplying the *time* of oscillation by the velocity, on the well-known principle that every kind of wave runs its own length during the time of one complete oscillation. The velocity is obtained by observing the time at different points. The time of oscillation is determined by means of tidal gauges. The tidal gauges established by the Coast Survey on the Pacific coast showed that the time of oscillation of the larger waves of the Japan earthquake was about thirty-three (thirty-one to thirty-five) minutes. This would give a wave-length of a little over 200 miles. It is probable that the wave-length in the case of the South American earthquake was at least equally great.

3. The distance to which the sea-waves run is far greater than that of the earth-waves. The former is distinctly sensible for 10,000 miles; the latter very rarely more than a few hundreds. There are two reasons for this: 1. All waves diminish in oscillation (wave-height) as they spread from the origin, because the quantity of matter successively involved in the oscillation constantly increases. But in the one case the matter involved lies in the circumference of a circle; in the other, in the surface of a sphere; therefore, the one increases as the distance, the other as the square of the distance. Therefore, the decrease of oscillation (height of wave) is far less rapid for water-waves than for elastic spherical waves. 2. A still more effective reason is this: Water-waves run in a perfectly homogeneous medium, and therefore diminish only according to the regular law just stated; but the earth-waves run in an heterogeneous, imperfectly elastic, and imperfectly coherent medium, and therefore they are rapidly quenched and dissipated by repeated refractions and reflections, and by repeated fractures of the medium and thus changed into other forms of force, as heat, electricity, etc. Were it not for for this, the destructive effects of earthquakes would be far more extensive.

4. We have said the wave-length remains unchanged. This length, therefore, represents the diameter of the original water-mound, and therefore of the original sea-bottom upheaval. In the Japan earthquake this was 200 miles across. This shows the grand scale upon which earthquake-movements take place.

5. Earthquake sea-waves differ from all other sea-waves in that their great size makes them drag bottom even in open deep sea. In their case, therefore, the velocity depends not only on the wave-length, but also *on the depth of the sea.* Knowing the size (wave-length) of these waves, and therefore what ought to be their *free velocity*, and also knowing their *actual velocity* by observation, the difference gives the *retardation* by dragging; and by the retardation may be calculated the mean depth of the ocean traversed. In this way it has been determined that the mean depth of the Pacific between Japan and San

Francisco is 12,000 feet, and between Peru and Honolulu, Sandwich Islands, 18,500 feet. The great importance of such results is obvious.

Depth of Earthquake-Focus.

The great obscurity which hangs about the subject of the interior condition of the earth and the ultimate cause of igneous agencies renders any positive knowledge on these subjects of peculiar interest. There can be little doubt that the phenomena of earthquake-waves, their form, their velocity, their angle of emergence, etc., if once thoroughly understood, would be a most delicate index of this condition, and a powerful means of solving many problems which now seem beyond the reach of science. Among problems of this kind none is more important, and at the same time more capable of solution, than the depth of the origin of earthquakes, and therefore presumably of volcanoes.

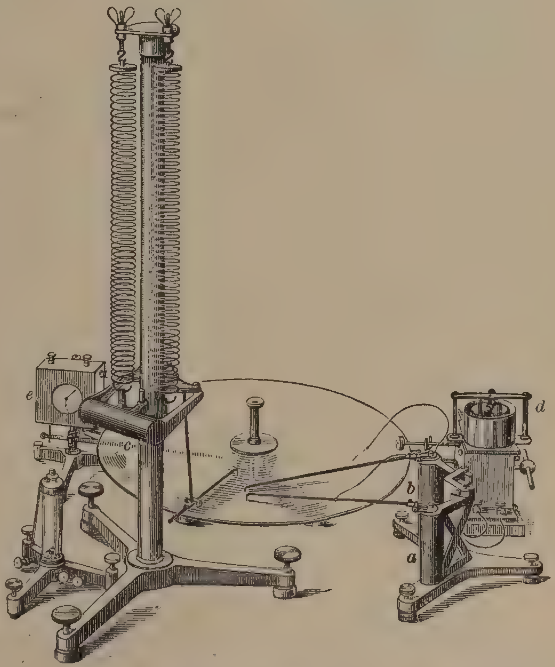

FIG. 108.—Ewing's Seismograph: *a* and *b*, horizontally oscillating pendulum; *c*, vertically oscillating pendulum; *d*, driving clock; *e*, time-recording clock. (Taken from a photograph of one at the University of California.)

Seismographs.—The most direct way of determining the depth of an earthquake-focus is by means of well-constructed seismographs. These are instruments for recording earthquake-phenomena. They are of infinite variety of forms, depending partly upon the facts desired to be recorded, and partly upon the mode of record. As examples we will mention only two:

An excellent instrument for recording slight tremors is one invented and used by Prof. Palmieri, of the Vesuvian Observatory. It consists of a telegraphic apparatus with the usual paper-slip and stile. The paper-slip, accurately divided into hours, minutes, and seconds, travels at a uniform rate by means of clock-work. The battery-circuit is closed and opened, and the recording stile worked by the shaking of a metallic bob, hung by a delicate spiral spring above a mercury-cup; the shaking of the bob being determined by the tremor of the earth. Such an instrument records the exact moment of occurrence of earthquake-shocks, however slight; also, the moment of passage of every wave and its time of oscillation; and if there be more than one such instrument, the moment of occurrence at different places gives the velocity of the surface-wave v'.

If we desire to record not only the *time* but also the *character* of the earth-movement, then a different kind of seismograph is necessary. The principle of all these is the principle of a pendulum. If we have a pendulum with a heavy bob swinging freely, when an earthquake arrives, the bob will stand still, while the earth moves beneath it. This *relative* movement of the pendulum may be recorded by suitable device. But an ordinary *freely* swinging pendulum moves often too largely, and continues its movement after the cessation of the cause. What we want is a pendulum which will stand indifferently in any position (astatic). One of the best forms of instrument yet devised is that of Prof. Ewing (Fig. 108). It consists essentially of *three* pendulums swinging in the manner of a bracket or a gate, and placed in three rectangular planes: (1) vertical, north and south, *a;* (2) vertical, east and west, *b;* and (3) horizontal, *c*. The horizontal one is retained in position by sensitive spiral springs. Stiles are fixed to these pendulums in such wise as to record on a circular smoked glass plate rotating in a horizontal plane. No. 1 records the east-and-west movement, No. 2 the north-and-south movement, and No. 3 the up-and-down movement. A clock is set agoing by the arrival of the earth-wave, and afterward marks seconds on the revolving smoked glass disk. Fig. 109 represents a portion of such record. These three records may be combined so as to show the actual amount and direction of the earth-movement (Fig. 99, p. 121).

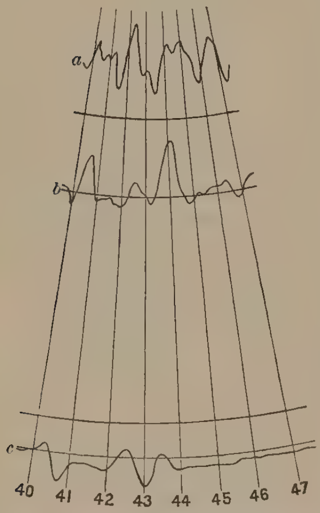

FIG. 109.—Record of a Ewing's Seismograph: *a*, east-and-west motion; *b*, north-and-south motion; *c*, up-and-down motion (after Sekiya).

The important facts recorded by this instrument are: 1. The *instant of transit;* 2. The *direction of transit;* 3. The direction of oscillation, or *angle of emergence;* 4. The *amount of oscillation.* From these elements (if we have several seismographs scattered about the country) may be calculated: 1. The *velocity of transit;* 2. The *position of the focus;* 3. Perhaps the *form of the focus*, whether point or fissure; 4. The *force of the original concussion.* The most important of these are the position and depth of the focus.

The Determination of the Epicentrum.—A good seismograph, or a number of these, will give the direction of transit of the surface-wave. If in this way, or even by rougher methods, we get a number of these *surface-lines of transit*, by following these back we get the epicentrum at their intersection. This is Mallet's method. Or if, by means of many seismographs giving time of transit, or even by observatories or stations of any kind with accurate clocks, we get several points of *simultaneous arrival* of the wave, then by drawing a curve through these points we have a coseismal curve. A perpendicular drawn from the middle point of the line joining any two of these points will pass through the epicentrum, and two such perpendiculars would determine its position. Fig. 110 represents coseismal curves, and *b*, *c*, *d*, three points on the curve; *a* is the epicentrum. This is Seebach's method. It gives good results if the curves be not too irregular.

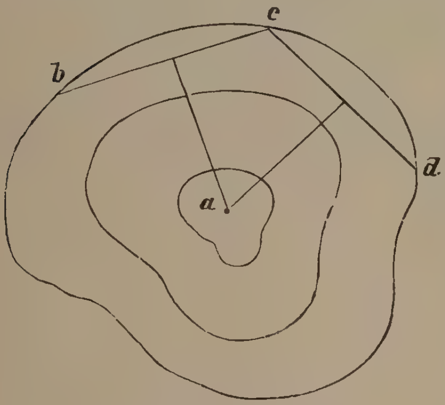

Fig. 110.—Coseismal Lines.

Determination of the Focus.—*Mallet's Method.*—The normal wave is a wave of longitudinal oscillation. The direction of oscillation, therefore, is the same as the direction of transmission (wave-path), which is the radius of the agitated sphere. If, therefore, the direction of the ground-motion be followed into the earth, it carries us back along the wave-path to its origin, the focus. Two such wave-paths by their intersection would determine its position. Thus, in Fig. 111, if *c* and *b* be the position of two seismometric observatories, the angles of emergence, *x c a* and *x b a*, being given by observation, and the distance, *c b*, being known, we have all the elements necessary to determine either by calculation or by accurate plotting the wave-

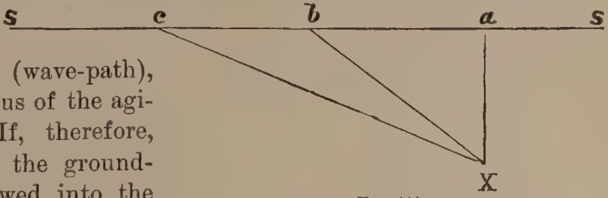

Fig. 111.

paths $c\,x$ and $b\,x$, and their point of intersection x, and therefore of the depth $a\,x$.

Seebach's Method.—Mallet's experiments (page 119) were undertaken in the hope that the relation of the velocities of the surface and spherical waves would at once, by simple calculation, give the depth of the focus, for by Hopkins's law *sec.* $E = \frac{v'}{v}$. It would do so if v were constant. But this is not true, and thus the method is valueless. But although it is impossible thus to find the depth *directly*, it may be found *indirectly*, as Seebach has shown, by the *rate* of decrease of the velocity of the surface-wave v', the rate being slower for deep earthquakes in proportion to the depth of their centrums. The rate of decrease by Hopkins's law follows the law of a hyperbolic curve, as shown in Fig 112, in which equal times are plotted on vertical, and spaces passed over in equal times on horizontal co-ordinates. In this hyperbolic curve horizontality, as at a, represents infinite velocity, and the velocity decreases as the angle increases up to 45°, when the velocity reaches its limit of equality with the velocity of the spherical wave v. The asymptote of the hyperbola passes through the focus of the earthquake.

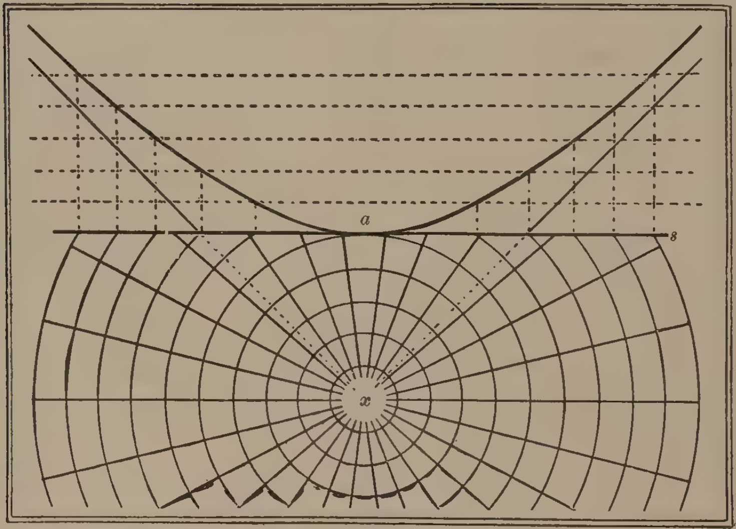

Fig. 112.—Diagram illustrating Hopkins's Law and Seebach's Method of Determining Focus of Earthquake.

Dutton's Method.—There is still another method, used by Major Dutton in his admirable discussion of the Charleston earthquake, and claimed by him as the most accurate of all. The *intensity* of the shock decreases from the epicentrum according to a certain law. The distance from the epicentrum of the place of most rapid decrease depends on the depth of the focus. If *s s* (Fig. 113) represent the surface of the earth, *x* the centrum, and *a* the epicentrum of an earthquake, then the curve $i\ i'\ i''$ will represent the law of variation of the intensity of the shock. Its height, as is seen, is greatest at the epicentrum and decreases in all directions. But at a certain distance, *d*, just where the curvature changes from convexity to concavity, the descent is steepest—i. e., the decrease is most rapid. This distance *ad* : the depth $a\,x : : 1 : \sqrt{3} : : 1 : 1{\cdot}73$. If the distance, *ad*, is known we easily find the depth, *ax*.

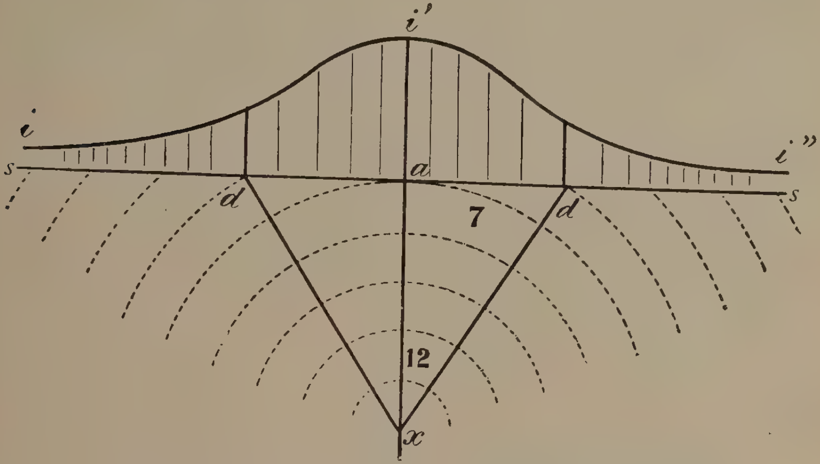

FIG. 113.—Diagram illustrating Dutton's Method of Determining Focus of Earthquake.

We have assumed the earth-waves as *normal*. We are justified in so doing, because this is the most decided wave, and soon outruns the transverse wave.

Although seismometers, such as we have described, are necessary for accurate results from few observations, yet by multiplying the observations, even by rough methods, approximative results may be obtained. We will mention several examples of determinations by these various methods.

In 1857 a terrible earthquake shook the territory of Naples, destroying many towns and villages and killing about 10,000 people. The scene of destruction was visited soon after by Mr. Mallet. By careful examination of overthrown objects, many lines of transit of the surface-wave were determined, which, protracted, carried him with considerable certainty to the epicentrum; similarly many lines of emergence, or paths of the spherical wave, protracted back, conducted to the focus.

This focus was determined to be not a point, but a *fissure, nine miles long and through three miles of solid rock.* The center of this rent was about six miles beneath the surface.* By somewhat similar methods the focus of the Japan earthquake of February 22, 1880, was found by Milne to be only three to five miles deep.† By his new method, viz., the *law of decrease of intensity of the shock-motion*, the focus of the Charleston earthquake of August, 1886, was found by Captain Dutton to be about twelve miles deep.‡ All of these earthquakes also seem to have originated in a fissure.

In 1874 a not very severe earthquake shook central Germany. It has been thoroughly investigated by Seebach. The epicentrum was determined with great precision by erecting perpendiculars to the bisected chords of the coseismal curves. The focus was determined by his method as a rent through four miles of rock, the center of the rent being nine or ten miles in depth.#

The velocity of transit of the waves of the Naples earthquake was 860 feet per second, or between nine and ten miles per minute; that of the earthquake of middle Germany was about twenty-eight miles per minute. The velocity of transit in the case of the Charleston earthquake is estimated as high as one hundred or even one hundred and eighty miles per minute.

All these methods for depth assume Hopkins's law, and are therefore vitiated by the important modifications introduced by Schmidt. By Schmidt's law the varying velocity of the surface-wave must be represented not by a simple hyperbolic curve, as Seebach supposes (Fig. 112), but by a double curve, as shown in the upper part of Fig. 98. We have already seen (page 119) that the velocity of the surface-wave is indeed infinite at the epicentrum and then decreases, but it soon reaches a minimum at *d*, and then *increases* again without limit. Therefore the curve representing it is at first horizontal, then rises gradually to a maximum inclination, and again more and more approaches horizontality.

It is evident, then, that our knowledge is not yet sufficient to determine the depth of the centrum with any degree of certainty. With more perfect knowledge, however, we may hope not only to determine this, but even to sound the interior of the earth, gauge its density, and determine its general constitution.

Effect of the Moon on Earthquake-Occurrence.—By an extensive comparison of the times of occurrence of several thousand earthquakes

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* Mallet, Principles of Seismology.

† Seismological Society of Japan; vol. i, Part II, p. 1.

‡ Science, vol. ix, p. 489, 1887.

Seebach, Das Mittel Deutsche Erdbeben.

with the positions of the moon, Alexis Perrey has made out with some probability the following laws: 1. Earthquakes are a little more frequent when the moon is on the *meridian* than when she is on the horizon. 2. They are a little more frequent at new and full moon (syzygies) than at half-moon (quadratures). 3. They are a little more frequent when the moon is nearest the earth (perigee) than when she is farthest off (apogee). Now, if these laws are really true, it would seem that there is a *slight* tendency for earthquakes to follow the law of tides: for the first law gives the time of flood-tide, and the second and third the times of highest flood-tide. It would seem, therefore, that the attraction of the sun and moon has a perceptible effect in determining the time of occurrence of earthquakes. Many geologists regard these laws, if established, as conclusive proof of the general fluid condition of the earth beneath a comparatively thin crust. This interior liquid they suppose to be influenced by the tide-generating forces of the sun and moon; but, if this were true, the effect ought to be far greater than we find it—i. e., the shock would occur always at high tide. Whatever be the interior condition of the earth, the effect of the moon on the meridian would be to *assist*, and on the horizon to *repress*, any force whatsoever tending to break up the crust of the earth and to produce an earthquake.

Relation of Earthquake-Occurrence to Seasons and Atmospheric Conditions.—By extensive comparison of earthquake-occurrence with the seasons, it has been shown that they are a trifle more frequent in winter than in summer. Constructing a curve representing the annual variation of earthquake intensity, this curve rises to its maximum in January and sinks to its minimum in July. But the difference is small.

Prof. Knott has recently suggested what seems a possible explanation of this, at least for Japan, where this relation is quite marked. During winter, there is high barometer—i. e., great atmospheric pressure over the whole of Northern Asia (Siberia), and low barometer over equatorial Pacific. In addition to this, the heavy winter snow-fall greatly increases the pressure over Siberia. In summer, the condition of things is reversed—the barometer is low and the snow is removed over Siberia, and the barometer is high over mid-Pacific. This change of excess of pressure from a large land-area to a large ocean-area back and forth, must tend to fracture the earth-crust, or to produce readjustment of previous fractures, along their dividing line, i. e., along the margin of the sea-basin. This is known to be the place of origin of most of the Japanese earthquakes. This would take place mainly in winter, if the tendency of the earth-forces producing earthquakes were to produce readjustment by *subsidence* of land or elevation of sea-bottom.

There is an almost universal popular belief in earthquake-regions that the occurrence is preceded by a still, oppressive state of the air. Although no scientific investigations have confirmed this impression, yet it seems quite possible and even probable that diminished atmospheric pressure, indicated by a low state of the barometer, may act as a determining cause of earthquake-occurrence, precisely as the position of the moon on the meridian. A fall of one inch is equivalent to a lifting of 1,000,000 tons per square mile from the surface pressure. In both cases, however, we must regard these not as true causes of earthquakes, but only as causes determining the moment of occurrence.

SECTION 4.—GRADUAL ELEVATION AND DEPRESSION OF THE EARTH'S CRUST.

Of all the effects of igneous agencies these are by far the most important. Although not violent and destructive like volcanoes and earthquakes, although indeed so little conspicuous as to be generally unobservable except to the eye of science, yet acting not paroxysmally but constantly, not in isolated spots but over wide areas and affecting whole continents, their final result in modifying the crust of the earth and making history is far greater than that of all other igneous agencies put together. It is probable that the same causes which are now at work gradually raising or depressing the earth's crust have during geological times formed the continents and the seas.

Elevation or Depression during Earthquakes.—We have already spoken (pages 114 and 115) of sudden elevations or depressions of great areas of country at the time of earthquake-occurrence in Hindostan, in the valley of the Mississippi River, and especially of the southern part of South America. It is not probable, however, that much is accomplished in this paroxysmal way. These cases are referred to in order to show the close connection of such sudden bodily movements, and therefore presumably, also, of the slower movements about to be described, with the causes and forces which produce earthquakes.

Movements not connected with Earthquakes—South America.—Besides the sudden elevation of Chili and Patagonia by earthquakes, the same countries show evidences of gradual elevation on a stupendous scale. The evidences are old sea-beaches, full of shells of species now living in the adjacent sea, far above the present water-level. These "*raised beaches*" have been traced 1,180 miles on the eastern shore and 2,075 miles on the western, and at different levels from 100 to 1,300 feet above the sea. More recently Alexander Agassiz has traced them by means of corals still sticking to the rocks to the height of nearly 3,000 feet.* It is not probable that all this movement took place during the present geological epoch, but it is the more instructive on that very account, since it shows the identity of geological causes with causes now in operation.

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* Proceedings of the American Academy of Sciences, vol. xi, p. 287, 1876.

Italy.—The most carefully-observed instance of gradual depression and elevation is that of the coast of Naples. Fig. 114 is a map and

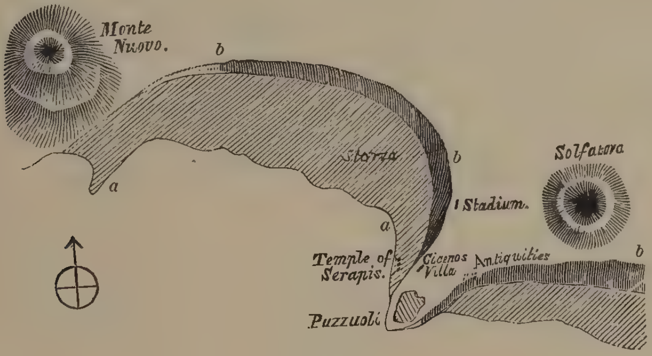

Fig. 114.

Fig. 115 a section of the coast of the bay of Baiæ, near Naples. Between *a a a*, the present coast-line, and the cliff *b b b*, which marks the position of the former coast-line, there is a nearly level plain called the Starza. Now, there is perfect evidence that at one time the land was depressed until the sea beat against the cliff *b b*, and that both the depression and the re-elevation to its present condition took place since the period of Roman greatness. The evidence is as follows:

1. There are certain shells abundant in the Mediterranean and in many other seas, called *lithodomus* (λίθος, a stone; *domus*, a house), from the habit of boring for themselves holes in the rocks near the water-line. Such borings, often with the dead shells in them, are found all along the base of the cliff *b b*, twenty feet above the present sea-level. 2. The level plain called Starza is composed of strata containing shells of the Mediterranean and Roman works of art. 3. On this plain, near the present sea-margin, are the ruins of a Roman temple dedicated to Jupiter Serapis. The floor and three of the columns *d* of this beautiful work are still almost perfect (Fig. 115). When first discovered the floor and the lower part of the columns were covered by the materials of the plain. Above the part thus covered the columns were bored with *lithodomi* to a height of twenty feet. This temple was, of course, above the sea-level during the Roman period. After that period it sank

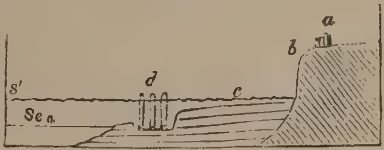

Fig. 115.

until the sea-level stood at s' (Fig. 115), twenty feet above the base. Since that time it rose to sea-level and is now again subsiding. These changes were so gradual that they were entirely insensible, and, in fact, unknown to the inhabitants. The upright position of the columns also shows that it could not have been produced by convulsive action. 4. Italian historians state that in 1530 the sea beat against the cliff *b b*. 5. Evidences of similar changes, in some cases depression and in others elevation, are seen in many places along the coast of Italy, Candia, and Greece.

In all the cases thus far mentioned, but especially that of the temple of Serapis, the near vicinity of volcanoes (Fig. 114) suggests that these effects were probably in some way connected with volcanic action. But there are many instances in which no such connection can be traced.

Scandinavia.—The best-observed instance of this kind is that of the coasts of Sweden. Careful observations on the coasts of the Baltic and Polar Seas have proved that nearly the whole of Norway and Sweden is rising slowly, and has been rising for thousands of years. South of Stockholm there is no elevation, but, on the contrary, slight *depression ;* but north of Stockholm the whole coast is rising at a rate which increases as we go north until it attains a maximum of five to six feet per century. These observations were made under the direction of the Swedish Government by means of permanent marks made at the sea-level, and examined from year to year. That similar changes have been in progress for thousands of years, and have greatly increased both the height and the extent of these countries, is proved by the fact that *old sea-beaches*, full of shells of species now living in the neighboring seas, are found fifty to seventy miles inland, and 100, 200, and even 600 feet above the present sea-level on both sides of the Scandinavian peninsula.* In some places, the country rock, when uncovered by removing superficial deposit of beach-shells, is found studded with barnacles like those which mark the present shore-line (Jukes).

The rising area is about 1,000 miles long north and south, and of unknown breadth. It may embrace a considerable portion of Russia. Lyell estimates the average rate as not more than two and a half feet per century. At this rate, to rise 600 feet would require 24,000 years.† Similar raised beaches are found in nearly all countries. We give these as examples of an almost universal phenomenon, which will be again more perfectly described in the chapter on the Quaternary.

Greenland.—For obvious reasons, evidences of *elevation* are much more conspicuous than evidences of *depression*. One of the best observed instances of the latter is that of the coast of Greenland. This coast is now sinking along a space of 600 miles. Ancient buildings on low rock-islands have been gradually submerged, and experience has taught the native Greenlander never to build his hut near the water's edge.

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* De Geer, Bulletin of the Geological Society of America, vol. iii, p. 65, 1892.

† Lyell's Antiquity of Man, p. 58.

Deltas of Large Rivers.—In the deltas of the Mississippi, the Ganges, the Po, and many other large rivers, there are unmistakable evidences of gradual depression. These evidences are fresh-water shells, and planes of vegetation, or *dirt-beds*, far below the present level of the sea. A section of the delta deposits of the Mississippi River reveals the fact that these deposits consist of river sands and clays, *s cl*, (Fig. 116), containing *fresh-water shells*, with now and then an intercalated stratum of marine origin, *l*, containing *marine* shells, and at uncertain intervals distinct lines *of turf* or *vegetable soil, g' g,''*, each with the stumps and roots of cypress-trees as they originally grew. Each one of these turf-lines is a *submerged forest-ground*, except the uppermost, which is the present forest-ground. Precisely similar phenomena have been observed in other large deltas. The deltas of the Ganges and the Po have been penetrated more than 400 feet without reaching bottom. In both the deposit is made up of fresh-water strata alternating with *dirt-beds* or forest-grounds. These facts prove that these great deltas have been at intervals during the whole period of their formation, as they are now, *fresh-water* swamps, overgrown in parts with trees, etc.; that they have steadily subsided to a depth indicated by the thickness of the deposit containing the old forest-grounds; that the up-building by river-deposit has gone on *pari passu*, so as to maintain nearly the same level all the time; but that from time to time the subsidence was more rapid, so that the sea gained possession for awhile until it was again reclaimed by river-deposit, and again more slow, so that the area was again thoroughly covered with forests, and so on. These facts are of great importance in geology, and will be again referred to in the following pages.

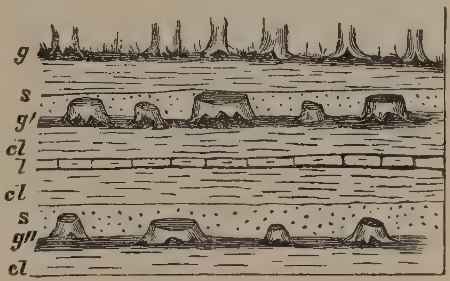

FIG. 116.

Southern Atlantic States.—Evidence of a similar kind proves that a large portion of the coasts of our Southern Atlantic States is slowly subsiding at the present time, though there are also evidences, in the form of raised beaches, of *elevation* immediately preceding the present subsidence. The evidences of subsidence are most conspicuous along the coast of South Carolina and Georgia. They consist of cypress-stumps *in situ* below the present tide-level. According to Cook, late Geologist of New Jersey, the coast from Long Island to Cape May is sinking at the rate of two feet a century.

These facts seem to point to the conclusion that subsidence is going on in nearly all places where large deposits of sediment are accumulating.

Pacific Ocean.—But by far the grandest example of subsidence known is that which has been going on for thousands, probably hundreds of thousands, of years, and is still going on in the mid-Pacific Ocean. The subsiding area is situated under the equator, and is about 6,000 miles long by about 2,000 to 3,000 miles wide. The evidence of the subsidence and its rate is entirely derived from the study of coral-reefs in this region. The further discussion of the subject will be deferred until we take up the coral-reefs.

Our examples, be it observed, are all taken from the vicinity of coast-lines, the sea-level being used as term of comparison. In the interior of continents, and in the midst of the sea where there are no islands, this means of detecting changes fails us, yet it is precisely there, i. e., in the middle of the rising or subsiding area, that the changes are probably the greatest. *In the case of continents*, however, as already explained on page 22, we have another test of crust-movements, viz., the phenomena of river-beds. In a rising area the rivers cut rapidly deeper; in a subsiding area they fill up their old beds and rise to higher level. In this way we know that the Plateau and the Sierra regions have greatly risen in comparatively recent times, and are still rising, while the New England region has recently subsided, though probably is not still subsiding. The evidence of this will be given hereafter.

Theories of Elevation and Depression.

It is evident that observation only determines changes of *relative* position of sea and land. These changes may be the result of rise and fall of sea, or rise and fall of land. The popular mind naturally attributes them to the rise and fall of the sea, as the more unstable element. But, by the principle of hydrostatic level, it is clearly impossible that the ocean should rise or fall *permanently* at one place without being similarly affected everywhere. It is certain, therefore, that the changes we have described above, being in different directions in different places, must be due to *movements of the solid crust*. Nevertheless, it is also true that any increase in the height and extent of the *whole amount of land* on the globe must be attended with a corresponding depression of the sea-bottoms, and therefore an actual subsidence of the sea-level everywhere. Hence, if it be true, as is generally believed, that the continents have been, on the whole, increasing in extent and in height, in the course of geological history, then it is true also that the seas have been subsiding, and that therefore the relative changes are the sum of these two.

Admitting, however, that the actual increase of land at the *present time* is imperceptible, or at least very small in comparison with the oscillatory movements described above, we may look upon the *sea-level as fixed;* this statement being sufficiently correct when regarding the subject from the physical point of view, though untenable when regarded from the geological point of view. Admitting, then, the fixedness of the sea-level, what are the causes of the gradual movements of the solid crust?

Babbage's Theory.—Babbage believed that, in the vicinity of volcanoes, the rise and fall of ground were due to the expansion and contraction of rocks by heating and cooling. The re-elevation of the temple of Serapis occurred apparently soon after the eruption which formed Monte Nuovo (Fig. 114). It is not improbable that this re-elevation was the result of the heating and vertical expansion of the rocks to great depth, caused by the eruption of the interior heat at this point. A very small elevation of temperature of rocks several miles thick would be sufficient to produce a vertical expansion of twenty feet.

Other cases, such as the rise of sea-margins at a distance from volcanic action, Babbage explains as follows: Large accumulations of sediments, such as occur generally on coasts, would cause a rise toward the surface of all the subjacent isogeotherms. This increase of temperature of the crust would cause a vertical expansion or swelling of the crust at that point, and a consequent rise above the sea-level.

The great objections to this theory, as applied to these latter cases, are: 1. The elevation of sea-bottom from this cause would not affect the contiguous land; and, 2. That the places where the greatest quantities of sediments are depositing (as, for instance, the deltas of great rivers) are places of *subsidence*, instead of elevation.

Herschel's Theory.*—Sir John Herschel assumes, as a general law—what has been proved in a great number of instances—that areas of great accumulation of sediment are areas of subsidence. He agrees with Babbage, that accumulation of sediments must cause an upward movement of the isogeotherms, but he differs from Babbage in believing that this invasion of sediments by the interior heat would produce *subsidence* instead of elevation. For, according to Herschel, the invasion of sediments by the interior heat would produce chemical changes, and sometimes even aqueo-igneous fusion. These chemical changes, whatever other effects they produce, would certainly change loose sediments into denser crystalline rocks (metamorphism), thus producing contraction instead of expansion. The accumulating sediment meanwhile would subside, by the pressure of its own weight, on the liquid or semi-liquid thus formed.

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* Herschel, Proceedings of the Geological Society, vol. ii, p. 548; and Babbage, ibid., p. 72.

Recent View.—Again: On the view that there exists a sub-crust layer of liquid or semi-liquid matter (page 89), not only would *loading* with sediment cause *subsidence* of marginal *sea-bottoms*, but also lightening by erosion would produce elevation of *land-surfaces*.

General Theory.—The theory of Babbage accounts with great probability for the rise of ground in the vicinity of volcanoes, and Herschel's theory accounts, perhaps, for the subsidence of deltas and other places where great accumulation of sediment occurs; and this latter theory has the additional advantage of accounting for metamorphism, and perhaps, also, for volcanic phenomena. But it is evident that some other and more general theory is necessary to account for those great inequalities of the earth's crust which form land and sea-bottom. For example: although loading with sediment may cause sea-bottoms to sink; and lightening by erosion may cause land-surfaces to rise, yet this does not at all explain how sea-bottoms and land-surfaces came to be such. These great inequalities must be originated by some other cause; loading and lightening only tend to maintain them. The formation of these must be a phenomenon somewhat different from those local oscillations which alone have been the subject of direct observation. Such general changes can only be the result of some general cause affecting the earth as a whole, as, for example, gradual unequal *contraction of the whole earth* consequent upon its secular cooling. The further discussion of this theory, however, belongs properly to the second part of this work.

CHAPTER IV.

ORGANIC AGENCIES.

As agents modifying the crust of the earth, *organisms* are, perhaps, inferior to the agents already mentioned (although the immense thickness and extent of limestone strata are a monument of their power in this respect); nevertheless, they are peculiarly interesting to the geologist as delicate indicators of climate, and recorders of the events of the earth's history. We will take up the subject of their agency under three heads, each having a separate application in interpreting the structure and history of the earth, viz.: 1. Vegetable Accumulations, to account for coal and bitumen; 2. Bog-Iron Ore, to account for iron-ores inclosed in the strata; 3. Lime Accumulations, to account for limestones, etc.

SECTION 1.—VEGETABLE ACCUMULATIONS.

Peat-Bogs and Peat-Swamps.

Description.—In humid climates, in certain places, badly drained and overgrown with moss and shrubs, a black carbonaceous mud accumulates often to great depths. This substance is called peat or turf, and such localities peat-bogs. The thick mass of vegetation which covers their surface, with its interlaced roots often forms a crust upon which a precarious footing may be found, but beneath this is a tremulous, semi-fluid quagmire, sometimes twenty to forty feet deep, in which men and animals, venturing in search of food, are often lost. These bogs are most numerous in northern climates. One tenth of the whole surface of Ireland, and large portions of Scotland, England, and France, are covered with peat. The bog of the Shannon River is fifty miles long and three miles wide; that of the Loire in France is 150 miles in circumference. Extensive bogs exist also in the northern portions of our own country. The amount of peat in Massachusetts alone has been estimated at more than 15,000,000,000 cubic feet (Dana). In California, an imperfect peat covers large areas about the mouth of the San Joaquin River and elsewhere (tule-lands). In more southern climates, where the conditions of humidity is present, immense accumulations of peat also occur—not, however, in bogs overgrown with moss and shrubs, but in extensive *swamps* covered with *large trees.*

Composition and Properties of Peat.—Peat is disintegrated and partially decomposed vegetable matter. It is composed of carbon, with small and variable quantities of hydrogen, oxygen, and nitrogen. It is, therefore, vegetable matter which has lost a part of its gaseous constituents, and in which, therefore, the carbon is greatly in excess. In more recent peat, the vegetable nature and structure are plainly detectable by the eye, but in older peat only by the microscope. In all countries where it occurs, it is dried and used as a valuable domestic fuel. By powerful pressure it may be converted into a substance scarcely distinguishable from some varieties of coal, and, thus changed, is now extensively used for all purposes for which coal is used, and has therefore become an important article of commerce.

Peat possesses a remarkable *antiseptic property.* This property is probably due to the presence of humic acid and of hydrocarbons analogous to bitumen, which are formed only when vegetable matter is decomposed in presence of *excess of water.* The bodies of men and animals have been found in bogs in a good state of preservation, which must have been buried many hundred years. In 1747, in an English bog, the body of a woman was found, with skin, nails, and hair, almost perfect, and *with sandals on her feet.* In Ireland, under eleven feet of peat, the body of a man was found *clothed in coarse hair-cloth.* Several other instances of bodies of men and animals, and innumerable instances of skeletons of animals, preserved in bogs where they have perished, might be mentioned. Large trunks of trees are often so perfectly preserved that they are used as timber, and stumps similarly preserved are found with their roots firmly fixed in the under-soil of the bog as if they had grown on the original soil on which the bog was accumulated.

Mode of Growth.—Plants take the greater portion of their food from the air, and give it, by the annual fall of leaf and finally by their own death, to the soil. Thus is formed the humus or *vegetable mold* found in all forests. This substance would increase without limit were it not that its decay goes on *pari passu* with its formation. But in peat-bogs and swamps the excess of water, and, still more, the antiseptic property of the peat itself, prevent complete decay. Thus each generation takes from the air and adds to the soil continually and without limit. The soil which is made up entirely of this ancestral accumulation continues to rise higher and higher, until the bog often becomes higher than the surrounding country, and, when swollen by unusual rains, bursts and floods the country with black mud. A bog is therefore composed of the vegetable matter of thousands of generations of plants. It represents so much matter withdrawn from the atmosphere and added to the soil. In some cases, besides the material deposited from the growth of vegetation *in situ*, the accumulation may be partly also the result of organic matter drifted from the surrounding surface-soil.

Rate of Growth.—The rate of peat-growth must be very variable, since it depends upon the vigor of the vegetation and upon the manner of accumulation, whether entirely by growth of plants *in situ*, or partly by driftage. Many of the European bogs are evidently the growth of not more than eighteen hundred years, for they were forests in the time of the Romans, or even later. The felling of these forests, as a military measure to complete the subjugation of the country, and the consequent impediments to drainage thus produced, have changed them into bogs. At their bottoms, and covered with eight to ten feet of peat, are found the trunks and the stumps of the original forests, the axes and coins of the Roman soldiers, and the roads of the Roman army. The rate of accumulation has been variously estimated, from one or two inches to several feet per century. In all cases of simple growth *in situ*, however, and therefore always in great peat-swamps, the increase is very slow.

Conditions of Growth.—The conditions usually considered necessary for the formation of peat are *cold* and *moisture;* and of these the former is considered the more important, as without cold it is supposed vegetable matter would be destroyed by decay. In proof of this it is stated that peat-bogs are more numerous in cold climates. But it is more probable that excess of moisture is the only important condition. This condition may be rarer in warm climates on account of the greater capacity of the air for moisture in these climates; but when it is present, immense accumulations of peat occur in extensive swamps. The *Great Dismal Swamp* is a good illustration. This swamp, situated partly in North Carolina and partly in Virginia, is forty miles long by twenty-five miles wide. It is covered with a dense forest of cypress and other swamp trees, by the annual fall of whose leaves the peat is formed. These trees, by means of their long tap-roots and their wide-spreading lateral roots, maintain a footing in the insecure soil, but are often overthrown, and add their trunks and branches to the vegetable accumulation. The original soil, upon which the accumulation was formed, must have been lower in the center, but the surface of the peat rises very gently toward the center, which is twelve feet higher than the circumference (Fig. 117). Near the center there is a lake of clear, wine-colored water, seven miles across and fifteen feet deep, the banks and bottom of which are composed of pure peat.

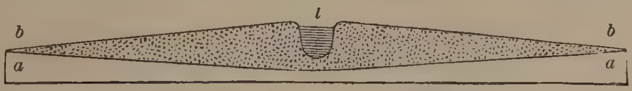

FIG. 117.—Ideal Section through Dismal Swamp: *a a*, original soil; *b b*, peat; *l*, lake.

In the Mississippi River swamps there are also large areas where pure peat has been accumulating for ages, and is still accumulating, by growth of trees *in situ*, though subject to the annual floods of the river. The *pureness* of the peat in these cases is due to the fact that the muddy waters of the river are strained of all their sedimentary matter by passing through the dense jungle-growth of cane and herbage which surrounds these favored spots. Thus only pure water reaches them.* Similar peat-swamps are found at the mouths of the Ganges, the Niger, and other great rivers.

Alternation of Peat with Sediments.—We have already stated (page 136) that a section of the delta-deposit of many great rivers, such as the Mississippi, Ganges, and Po, reveals alternate layers of fresh-water and marine sediments, with thin layers of vegetable mold containing stumps. In some cases these layers of vegetable mold amount to considerable thickness of turf or peat. Layers of peat two feet thick have been found between layers of river-mud in the delta of the Ganges (Lyell's Principles of Geology). Similar layers have been found in the delta of the Po. They are evidently *submerged peat-swamps*. These facts are of great importance in the explanation of the accumulation of coal.

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* Lyell's Elements of Geology, fifth edition, p. 385.

Drift-Timber.

Great rivers in wooded countries always bring down in large numbers the trunks of trees torn from the soil of their banks. These trunks lodging near their mouths, where the current is less swift, and accumulating from year to year, form *rafts* of great extent. The great raft of the Atchafalaya, which was removed in 1835 by the State of Louisiana, was a mass of timber ten miles long, seven hundred feet wide, and eight feet thick. It had been accumulating for more then fifty years, and at the time of its removal was covered with vegetation, and even with trees sixty feet high. Similar accumulations of driftwood are described as occurring in the Red River, the Mackenzie River, and in Slave Lake. Such rafts become finally imbedded in river-mud, and undergo a slow change into lignite or imperfect coal. Beds of partially-formed lignite are therefore found in sections of the delta-deposit of almost all great rivers. We will use these facts in speaking of the theories of the coal.

SECTION 2.—BOG-IRON ORE.

At the bottom of peat-bogs is often found a "*hard pan*" of iron-ore, sometimes one to two feet thick. The same material often collects in low spots, even when there is no decided bog. The manner in which this iron-ore accumulates is very interesting, and in a geological point of view very important.

Peroxide of iron exists very generally diffused as the red coloring-matter of soils and rocks. In this form, however, it is insoluble, and therefore can not be washed out by percolating waters. For this purpose the agency of decomposing organic matter, present in all percolating waters, is necessary. Decomposition of organic matter is a process of oxidation. In contact with peroxide of iron (ferric oxide) it deoxidizes, and reduces it to *protoxide* (ferrous oxide). The acids, especially carbonic acid, produced by decomposition of the organic matter, then unite with the protoxide, forming carbonate of iron. The carbonate, being soluble in water containing excess of carbonic acid, is washed out, leaving the soils or rocks decolorized, and the iron-charged waters come up as chalybeate springs. But the ferrous carbonate rapidly oxidizes again in the presence of air, by exchanging its carbonic acid for oxygen, and returns to its former condition of ferric oxide, and is deposited. Thus all about iron springs, and in the course of the streams which flow from them, and in low places where their waters accumulate, we find reddish deposits of hydrated *ferric oxide.* This is the most common but not the only form. For if the iron-waters accumulate, and the iron be deposited in the presence of excess of organic matter, as peat, then the iron is not (for in the presence of this reducing agent it can not be) reoxidized, but remains in the form of *ferrous carbonate.*

Thus there are two forms in which iron leached out from the soils and rocks may accumulate, viz., ferric oxide and ferrous carbonate: the former is accumulated where the organic matter is in small quantities, and consumes itself in doing the work of dissolving and carrying; the latter where the organic matter is in excess.

Many familiar phenomena may be explained by the principles given above: 1. Clay containing both iron and organic matter is never red, but always blue or slate-colored, because the iron is in the form of ferrous carbonate and ferrous sulphate; but the same clay will make good red brick, because by burning the organic matter is destroyed and the iron peroxidized. 2. In *red-clay* soils, such as those of our primary regions, the surface-soil, especially in forests, is always decolorized, the coloring of peroxide of iron being washed out and carried deeper by water containing organic matter derived from the vegetable mold. 3. In sections of red clay, at the sides of gullies or railroad-cuttings, along every fissure or crevice through which superficial waters percolate, the clay is bleached. The marbled appearance of red clays is also probably due, in a great measure, to the irregular percolation of superficial waters containing organic matter. 4. The under clay or sand of peat-bogs is usually decolorized.

We will hereafter make use of these facts and principles in the explanation of beds of iron-ore.

Section 3.—Lime Accumulations.

Coral Reefs and Islands.

Interest and Importance.—The subject of corals and coral reefs is one of much popular as well as scientific interest. The strange forms and often splendid colors of the living animals; the number and extreme beauty of the coral islands which gem the surface of certain seas; the large amount of habitable land which owes its existence to the agency of these minute animals; the fact that a large area, probably several thousand square miles, has been thus added to our own territory; the great dangers connected with the navigation of coral seas, strikingly displayed on our own coast by the fact that the considerable town of Key West is almost wholly dependent on the wrecking business for its existence—these and many other facts invest the subject with popular interest, while the great importance of corals as a geological agent gives the subject a scientific interest no less strong.

Coral Polyp.—The animal which secretes coralline stone is no insect, as generally supposed, but belongs to one of the lowest divisions of the animal kingdom, viz., the class of polyps. Like most of the lowest animals, it is composed of soft, gelatinous, and almost transparent tissue. The animal, however, has the power of extracting carbonate of lime from sea-water, and depositing it within its own body. The lime carbonate is deposited only in the lower portion of the animal, leaving thus the upper part and the tentacles free to move. The radiated structure of the polyp is perfectly reproduced in the coralline axis. This is a purely vital function, having no more connection with volition than the secretion of the shell of an oyster or the bones of the higher animals. The limestone thus deposited within the animal constitutes 90 to 95 per cent of its whole weight.

Compound Coral, or Corallum.—A single coral polyp is very small, but, like many of the lower animals, it has the power of multiplying indefinitely by buds and branches. Thus are formed compound corals. These may branch profusely, and then may be called *coral-trees;* or may grow in hemispherical masses, and are then called *coral-heads.* Coral-trees are sometimes six or eight feet high, and coral-heads fifteen to twenty feet in diameter. They consist of millions of individual coral polyps. Only the upper and outer portions of a coral-tree, and outer portion of a coral-head, are living; the lower and interior portions consist only of coralline lime-stone without life.

Coral Forests.—Coral polyps, however, reproduce not only by budding, but also by eggs. These eggs have the power of locomotion. As soon as they are extruded, they swim and float away, and, if they fall on sea-bottom favorable for their growth, they soon form first a coral polyp, and finally a coral-tree or coral-head. Thus from one coral-tree other coral-trees spring up all around and form a *coral forest*, which spreads in every direction where they find conditions favorable.

Coral Reef.—Finally, the limestone accumulation of thousands of successive generations of coral forests growing and dying on the same spot, together with the shells of mollusks and the bones of fishes which live in swarms preying on the corals, the whole, of course, crowned with the living forest of the present generation, constitute the *coral reef.* It is evident, then, that a reef is formed somewhat after the manner of a peat-bog. As a peat-bog represents so much matter taken from the air, so a coral reef represents so much matter taken from the sea-water. As each generation adds itself to the ancestral funeral-pile, the ground upon which the corals grow steadily rises until it becomes elevated far above the surrounding sea-bottom.

Coral Islands.—These are due to the action of waves upon the coral reefs. We have already seen how low islands are formed on submarine banks by this agency. Now, reefs are also a kind of submarine bank. On these, therefore, islands are also formed by waves. Fig. 118 represents an ideal section across a reef, as it would be if no wave-action interfered, *l l* being the sea-level. But by the action of the beating waves during storms large masses of reef-rock, often six or eight feet in diameter, or great coral-heads, are broken off from the outer or seaward side of the reef and rolled over to the leeward side. These form a nucleus about which collect similar or smaller fragments, and among these still smaller fragments, and these again are filled in and made firm with coral-sand, and the whole cemented into solid limestone rock (breccia) by the carbonate of lime in the sea-water.

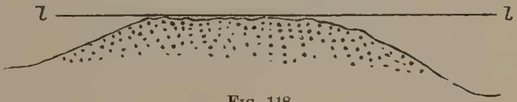

FIG. 118.

Islands thus formed, like all wave-formed islands, are low (twelve to fifteen feet high) and narrow (one quarter to one half mile wide), but long in the direction of the reef. They are at first perfectly bare, but become in time covered with vegetation, and even teeming with population. They are celebrated for their gem-like beauty. The final result is shown in ideal section in Fig. 119, in which the dotted portion is reef-rock, the strong waving line the surface of the living reef, and the shaded portion the island.

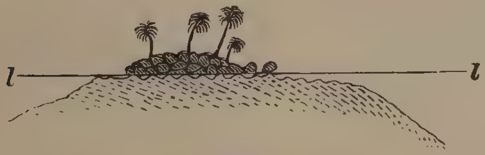

FIG. 119.

Conditions of Coral Growth.—Reef-building corals do not grow in all seas, nor over the whole bottom of the sea indiscriminately, but are confined to certain seas, and in these to certain spots and lines. The conditions of the growth are:

1. *A Winter Temperature of* 68°.—This condition confines them almost entirely to the torrid zone. The most marked exception to this is on the Florida coast and the Bahamas, where corals extend to 28° north latitude, and in the Bermudas to 32° north latitude. This extension of the usual limits of reef-building corals is due to the warm tropical waters carried northward by the Gulf Stream.

2. *A Depth of not more than One Hundred Feet.*—This condition confines them to submarine banks, and especially to the shores of continents and islands.

3. *Clearness and Saltness of the Water.*—On account of this condition corals will not grow on muddy shores, nor off the mouths of rivers, being destroyed by the fresh and muddy water.

4. *Free Exposure to Waves.*—Some species of corals grow in still water, but the strongest reef-building species delight in the dash of the surf. They will even flourish and build an almost perpendicular wall in breakers which would wear away the hardest rock. The reason is, that the immense profusion of life on a reef rapidly exhausts the water of the oxygen necessary for respiration, and of the carbonate of lime necessary for their stony structure, and therefore constant change of water is necessary.

All the conditions mentioned above apply only to reef-building species. Some corals live in temperate regions, some in very deep water, and some in sheltered places.

Pacific Reefs.—The reefs of the Pacific Ocean are of three general kinds, viz., *fringing reefs*, *barrier reefs*, and *circular reefs* or *atolls*. We will describe these in the order mentioned.

Fringing Reefs.—In the tropical Pacific every *high* island or previously-existing land of any kind is surrounded by a reef which attaches itself to the shore-line, and extends outward on every side just beneath the water-level, as far as the condition of depth will allow, thus forming a submarine platform bordering the island or other land. At the outer margin of this platform the bottom drops off very suddenly, forming a slope of 50° to 60°, and sometimes almost perpendicularly. The position and extent of the coral platform is indicated to the eye of the observer by a white sheet of breakers which surrounds the island like a snowy girdle, and extends some distance from the shore-line (Fig. 120). The section Fig. 121 will give a clear idea of the contour of land and sea-bottom. In this and the following sections the dotted parts represent coral formation. If the island is large, and considerable rivers flow into the sea, breaks in the reef platform will occur opposite the mouths of the rivers, the corals in these places being destroyed by the fresh, muddy waters. In the case of fringing reefs no islands are formed by the action of waves, but only a shore-addition to the original island, as shown at *a a* in the section.

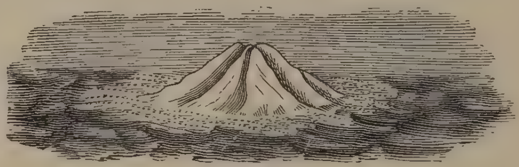

FIG. 120.

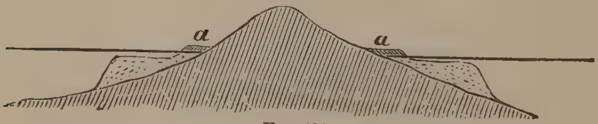

FIG. 121.

Barrier Reefs.—In many cases besides the fringing reef there is another reef surrounding the island like a submarine rampart at the distance of from ten to fifty miles. As the reef rises nearly to the surface of the sea, its position is indicated by a snowy girdle of breakers surrounding the island at a distance, and this snowy girdle is gemmed with wave-formed green islets. Within this girdle, and between the rampart and the island, there is a ship-channel twenty or thirty fathoms deep (Fig. 122). Through breaks in the coral rampart ships enter this channel and find secure harbor in a stormy sea. The section Fig. 123 will give a clear idea of the conformation of bottom. On the landward side of the coral rampart the slope of the bottom is gentle, but on the seaward side it is very steep, so that it is almost unfathomable at a short distance from the reef.

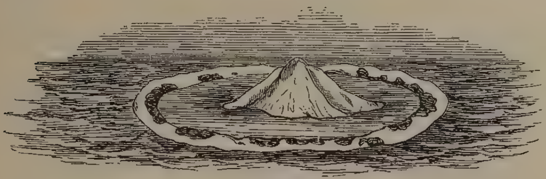
FIG. 122.

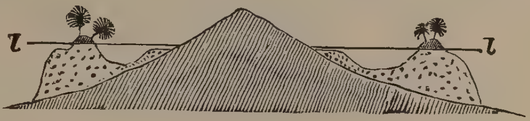

FIG. 123.

Circular Reefs or Atolls.—These are the most wonderful of the reefs of the Pacific. In a circular reef there is no volcanic island or other visible land to which the reef is attached. Imagine a circular line of breakers like a snow-wreath on the sea, indicating a circular submarine ridge (the coral reef) gemmed as before with wave-formed islets; and within the circle a lagoon of placid water twenty or thirty or even sixty* fathoms deep (Fig. 124). It is a submarine urn standing in unfathomable water, as seen in the section Fig. 125. Through breaks in the reef ships enter the charmed circle and find safe harbor. By means of

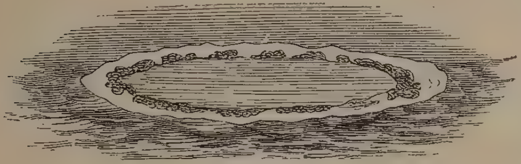
FIG. 124.

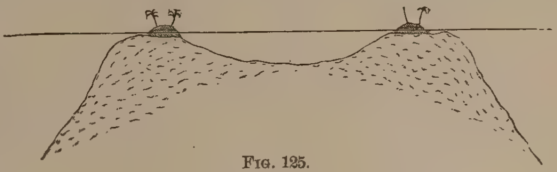
FIG. 125.

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* Sollas, Nat., 48, 575, 1893.

sounding it is found that on the interior or lagoon side the slope of the bottom is very gentle, but on the outer or seaward side is very steep, often 50° to 60°, and sometimes in places almost perpendicular to very great depth. Fig. 126 gives a perspective view, and Fig. 127, *a*, a map view, of an atoll, showing the irregular circular form of the reef and the little islands which gem its surface.

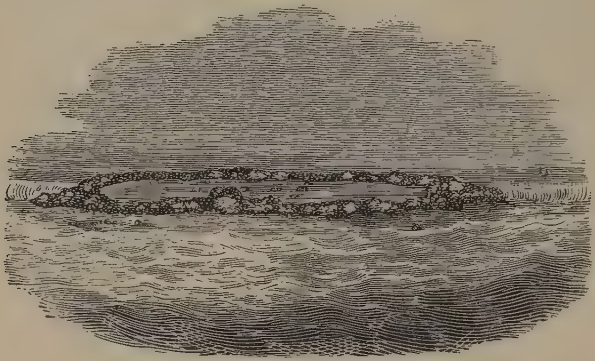

Fig. 126.—View of Whitsunday Island.

Small Atolls and Lagoonless Islands.—Besides the atolls already described, there are others, evidently of similar origin, but much smaller, in which the land is continuous. Sometimes the continuous line is open on one side (Fig. 127, *b*), and the lagoon is still in connection with the open sea. Sometimes the circle of land is complete, and the lagoon is isolated from the sea (Fig. 127, *c*). Sometimes the lagoon closes up, and a lagoonless island is the result (Fig. 127, *d*). These different forms graduate into one another and into the typical atoll.

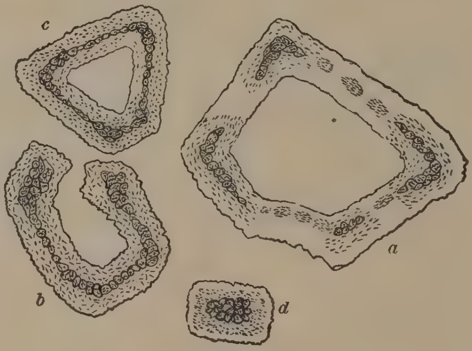

Fig. 127.

Theories of Barrier and Circular Reefs.

Fringing reefs require no theory. Corals attach themselves to the shore-line because they find there the depth necessary for their growth, and they extend outward until they are limited by the increasing depth. But there is a real difficulty in explaining barriers, for they seem to rise from water too deep for coral-growth; and the difficulty becomes still greater in the case of circular reefs or atolls, for these seem to have no connection with any pre-existing land, but to grow up from an unfathomable bottom. These latter, by their singularity and extreme beauty, have always attracted the attention and excited the wonder of Pacific travelers; and to their explanation theories have been principally addressed.

Crater Theory.—This theory supposes that an atoll is an extinct submarine volcano, the lagoon being the crater and the reef the lip or margin of the crater; that corals finding on this circular rim the conditions of depth necessary for their growth, occupy and build upon it to the surface of the water, after which, of course, waves finish the work by beating up the islets. The incredible supposition that thousands of these volcanoes should have come within 100 feet of the surface, and yet none of them appear above the surface, is not necessary; for we may suppose that many of them were originally above the surface, but, being composed of ashes and cinders, have been washed down by the waves. In 1831 a volcano burst forth in the Mediterranean and quickly formed an island of cinders and ashes, called Graham's Island. In a few months this island was entirely washed away by the waves, and only a circular submarine bank remained. If corals grew in the Mediterranean, there seems no reason why a circular reef should not have been formed.

Objections.—Even in its most plausible form, however, this theory is very improbable as a general explanation of atolls: 1. The great size of some of these atolls—thirty, sixty, and even ninety miles in diameter; and, 2. The high angle of the slope of these submarine mountains—50° to 60° or more—seem inconsistent with their volcanic origin. 3. This theory offers no explanation of the barrier reefs, and yet it is possible to trace every stage of gradation between barriers and atolls, showing that they are due to similar causes.

Subsidence Theory of Darwin.—This theory explains not only atolls, but also barriers, and connects both in a satisfactory manner with fringing reefs. It supposes that the sea-bottom, where atolls and barriers occur, has been for ages subsiding, but at a rate not greater than the upward building of the coral-ground; that every reef commences as a fringing reef, but, in the progress of subsidence, was converted first into a barrier and finally into an atoll. For, as the volcanic island went down, the corals would build upward on the same spot; and as the island would become smaller and smaller, and the corals would grow faster on the outer side of the reef, where they are exposed to the breakers, it is evident that the reef would become separated from the island by a ship-channel, and thus become a barrier. Finally, when the island disappears entirely, the reef, still building upward, would become an atoll. These changes are represented in the accompanying section (Fig. 128). As the changes are relative, they may be represented either by the land sinking or the sea-level rising; for the sake of convenience we use the latter. In the figure, $l'' \, l''$

represents the sea-level when the reef was a *fringe*, $l' \, l'$ when it was a *barrier*, and $l \, l$ the present sea-level, when it has become an atoll. The ship-channel and the lagoon, though always lower, rise *pari passu* with the reef proper. This is the result partly of the growth of placid-water species of corals, and partly of the drifting of coral *débris* from the reef, and detritus from the volcanic island. It is seen that the corals do not build a vertical wall, and therefore that the atoll is always smaller than the coast-line of the original island. Consequently, if the subsidence continues, a typical atoll is changed into a small closed lagoon, and, finally, into a lagoonless island. These, therefore, indicate the deepest subsidence.

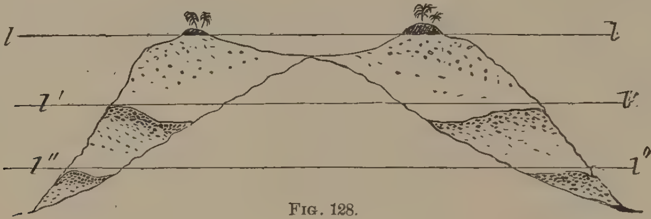

Fig. 128.

Evidences.—1. This theory accounts for all the more obvious phenomena of atolls, such as their irregular circular form, their size, the steepness of their outer slopes, etc. 2. Every stage of gradation between the fringing reef on the one hand, and the atoll on the other, has been traced by Dana, strongly suggesting that they are all different stages of development of the same thing. We have in the Pacific some high islands, which are surrounded by a pure fringing reef; others in which the reef is a fringe on one side and a barrier on the other; others in which the barrier is one mile, two miles, five miles, ten miles, twenty, or thirty miles distant; others which are called atolls, but the point of the original volcanic island is still visible in the middle of the lagoon; others which are perfect atolls, but, by sounding, the head of the drowned volcanic island is still detectable. The next step in the series is the perfect atoll, then the small atoll, and, finally, the lagoonless coral island. These last kinds show that the original island has gone down deeply. 3. By grappling-hooks *dead* coral-trees have been broken off and brought up from the ground where they once grew, now far below the limiting depth of coral-growth. The evidence of subsidence in this case is of the same kind and force as that derived from the submerged forest-ground (page 143). The corals have been carried below their depth and drowned. 4. The remarkable distribution of the various kinds of reefs brought to light by Dana is satisfactorily explained by this theory, and therefore is an argument in its favor. In the middle of the atoll region of the Pacific there is a *blank area*, 2,000 miles long and 1,000 or more miles wide, where there are no islands. Next about this is an area in which *small atolls* predominate; about this again the region of ordinary atolls; beyond this the region mostly of barriers, and finally of fringes. Now, by this theory this distribution is thus explained: The sea-bottom in the blank area has gone down so fast that the corals have not been able to keep pace, and have therefore been drowned, and left no monument of their existence. In the next region the corals have been able to keep within living distance of the surface, but the original islands have not only disappeared, but gone down to great depths. In the next the original high islands have disappeared, but not gone down so deep; in the next they have sunk only to the middle. The fringing reefs stand on the margin of the sinking area. Outside of this again there is in some places even evidence of upheaval instead of subsidence. Raised beaches in the form of fringing-reef rocks are found clinging to the sides of high islands many feet above the present sea-level. 5. In some places this subsidence seems to be still in progress. On certain coral islands sacred structures of stone made by the natives are now standing in water, and the paths worn by the feet of devotees are now passages for canoes (Dana). According to this view, therefore, an atoll is the site of a drowned island.

Murray's Theory.—Recently serious doubts have been cast on Darwin's subsidence theory, at least as a universal explanation of barriers and atolls.* Mr. Murray, from his observations during the voyage of the Challenger, believes that barriers and atolls may be explained without subsidence of the sea-floor. An outline of his views may be thus stated: 1. Submarine banks formed in any way, either (*a*) built up by accumulating shells of successive generations of marine animals, until within the reach of coral-growth; or (*b*) by volcanic cinder cones cut down by the waves so as to form suitable banks. 2. The bank thus formed, taken possession of by corals, is built up to the sea-level, and thus forms a small island. 3. The coral-growth is confined, or at least most rapid, on the outer margin, because exposed to the action of the sea. Thus arises a ring with blank space within. 4. The action of waves beats these rings into a series of islets. 5. Meanwhile the scouring action of currents and the solvent action of sea-water scoops out the blank area into a more or less deep lagoon. 6. The action of waves breaking the living coral and the reef-rocks forms a *débris*-pile or talus, with steep outward slope, on which the corals continue to grow seaward into deep water. Thus the coral ring continues to spread, like a *fairy ring*, by growing seaward in every direction and dying behind. 7. According to Darwin, atolls grow continually smaller; according to Murray, they grow continually larger. According to the one, the lagoonless islands are the last *remnants* of drowning islands; according to the other, they are the *beginnings* of new islands.

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* The author of this volume believes that he was the first who showed, in the case of the Florida reefs, how barriers may be formed without subsidence. American Journal of Science and Art, vol. xxiii, p. 46, January, 1857.

Barriers are similarly explained. They commence as fringes, which grow seaward as far as depth will allow. Then the corals die near the shore, and this part is scoured out into a channel. Meanwhile the reef extends seaward on its own talus, and the channel is *pari passu* widened.

Perhaps the chief objection to Murray's views is the depth of some lagoons and channels. It seems improbable that the solvent and scouring action of the sea should extend to such depth. On the contrary, the lagoons are more apt to fill up than to deepen unless by subsidence.

In the present condition of the question it is probable that there are more ways than one in which barriers and atolls may be formed, but Darwin's view seems still to hold its own as a general, though not as a universal theory.

On Darwin's view, of course, every atoll marks the site of a sunken volcanic island. It will be interesting, therefore, to make some estimates based on this view.

Area of Land Lost.—Probably several hundred thousand square miles of habitable high land has been lost by this subsidence. The actual extent of atolls known is at least 50,000 square miles. But this is far less than the loss of high land. For—1. It is certain that the area of an atoll is always less than that of the original fringe or base of the original high island, for the outer wall of an atoll is not perpendicular. The contraction continues as the subsidence progresses, until small atolls or only lagoonless islands remain. 2. An immense lost area is represented by the space between *barriers* and their high islands. The great Australian barrier extends along that coast 1,100 miles, at an average distance of thirty miles, with a ship-channel between of thirty to sixty fathoms deep. This single barrier, therefore, represents a lost land-area of 33,000 square miles. 3. In the blank area already spoken of, probably many islands went down, and left no record behind.

The large amount of high land thus lost has been replaced only to a small extent by the wave-formed coral islets on the reefs.

Amount of Vertical Subsidence.—The amount of subsidence may be estimated by the distance of barriers from their high islands, or by soundings off atolls, to ascertain the height of these coral mounds, or by the average height of the high islands of the Pacific. 1. The average slope of the high islands of the Pacific is about 8°. Now, assuming this slope (Fig. 129), a barrier, d, at the distance of five miles would be 3,700 feet thick, and would represent a subsidence nearly to that extent (Rad. : tan. 8° :: $a\,d : d\,b$); a distance of ten miles would represent a vertical subsidence of 7,400 feet. Many barriers are at much greater distance. 2. Off Keeling atoll, 6,600 feet, a line of 7,200 feet found no bottom (Darwin). Near other atolls a depth of 3,000 feet has been found (Dana). 3. The average height of the high islands of the Pacific can not be less than 9,000 feet (Dana); some of them reach nearly 14,000 feet. It is very improbable that, among the hundreds of atolls known, not one of their high islands should have reached the average elevation of 9,000 feet. Yet these have entirely disappeared, and not only so, but the small atolls and lagoonless islands, and more especially the blank area, would seem to indicate that they have disappeared to great depths. For these reasons, it is almost certain that the extreme subsidence has been at least 9,000 feet. We will take 10,000 feet as the most probable extreme subsidence.

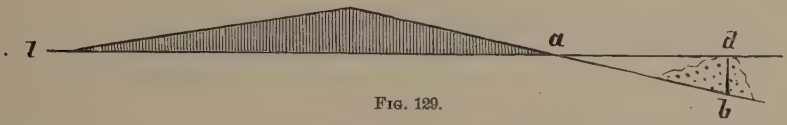

FIG. 129.

Rate of Subsidence.—The rate of subsidence may have been to any degree less, but can not have been greater, than the rate of coral *ground-rising;* for otherwise the corals would have been carried below their depth and drowned. It is difficult to estimate the rate of coral ground-rising, but the only basis of such estimate is the rate of coral-growth. Of the observations on this point we select two, one of them on the head-coral (meandrina), the other on the staghorn-coral (madrepore):

1. On the walls of the fort at the Tortugas, Florida, meandrina commenced to grow, and in fourteen years the crust had become only one inch thick. Agassiz takes one inch in eight years as a probable rate under favorable circumstances. This would be one foot in a century. As this is a head-coral, the coral-growth may be taken as the measure of the reef ground-rising.

2. In examining the reefs about the Tortugas in the winter of 1851, an extensive grove of madrepore was found in the comparatively still water on the inside of the outer reef, in which the thick-set prongs had grown, year after year, to the same level, and were successively

killed. The mean level of the water here is lower during the winter, by about a foot, than during the summer. The falling of the water annually *clips* this grove at the same level. Now all the prongs at this level were dead for about three inches. Evidently, therefore, this is the annual growth of madrepore-prongs.* But in branching corals the rate of point-growth is very different from the rate of ground-rising. If all the points of a madrepore be cut off three inches, then ground into powder, and the powder strewed evenly over the ground shaded by the coral-tree, the elevation thus produced would correctly represent the annual rate of reef ground-rising for this species. A quarter of an inch would probably be a full estimate. This would make two feet for a century. One foot to two feet per century is, therefore, probably about the rate at which coral ground rises. As already stated, the rate of subsidence may be less, but can not be greater, than this.

Time involved.—At this rate 10,000 feet of vertical subsidence would require 500,000 to 1,000,000 years. How much of this belongs to the present geological epoch it is impossible to say. Dead corals, indentical with those still living on the reefs, have been brought up from a depth of 250 feet, but, as this is only 150 feet below the limit of coral-growth, it would require only 75 to 150 centuries. The process probably commenced in previous geological epochs, and has continued to the present time. This is, therefore, an admirable example of geological agencies still at work.

Geological Application.—The facts brought out in the preceding pages are of great importance in geology.

1. We have here the most magnificent example of subsidence still in progress. The subsiding area has not been accurately defined, but it probably covers nearly the whole of the intertropical Pacific. According to Dana, estimated by the atolls alone, it is 6,000 miles long and 2,000 miles wide; but if we take into account also *barriers*, which are equally certain evidences of subsidence, it extends east and west from the extreme of the Paumotu group on the one side to the Pelews on the other, and north and south from the Hawaiian group to the Feejees, making an area of not less than 20,000,000 square miles. Now, it is evident that there must have been, as a correlative of this extensive and *permanent* downward movement, an equally extensive permanent elevation of the earth's crust somewhere else. Dana thinks its correlative is found in the extensive elevations of the Glacial epoch, and therefore that the whole work was accomplished *since the Tertiary*. But it is more probable that this correlative is found in the

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* See full account of these observations in American Journal of Science and Arts, vol. x, p. 34.

gradual bodily upheaval of the whole western side of the continent, especially in the Rocky Mountain region, which commenced after the Cretaceous.

2. We have here the formation of limestone rocks of various kinds going on before our eyes over immense areas and several thousand feet in thickness, and we learn thus that limestones are of organic origin.

3. The character of the rocks thus formed is very interesting to the geologist. In some places, as we have already seen, it is a coarse conglomerate, or *breccia*, composed of fragments of all sizes cemented together (*island-rock*); in some places it is made up entirely of rounded granules of coralline limestone (*coral-sand*), cemented together (*shore-rock*), and forming a peculiar oölitic rock (ὤον λίθος, *egg-stone*). But the larger portion of the reef ground is a fine compact limestone, made up of comminuted coralline matter (*coral mud*), cemented together (*lagoon-rock*). This fine coral mud is carried by waves and tides into the lagoon, and serves to raise its bottom: it is also carried by currents and distributed widely over the neighboring sea-bottoms. Soundings in coral seas bring up everywhere this final coral mud, showing that compact limestone is now forming over wide areas in coral seas. The reef-rock, as already stated, has been found clinging to the sides of high islands, having been elevated many feet above sea-level; in other cases atolls have been elevated 250 feet above the sea-level. The structure of the reef-rock has thus been exposed to view. In some places it contains imbedded remains of corals and shells, but in other parts it is entirely destitute of these remains.

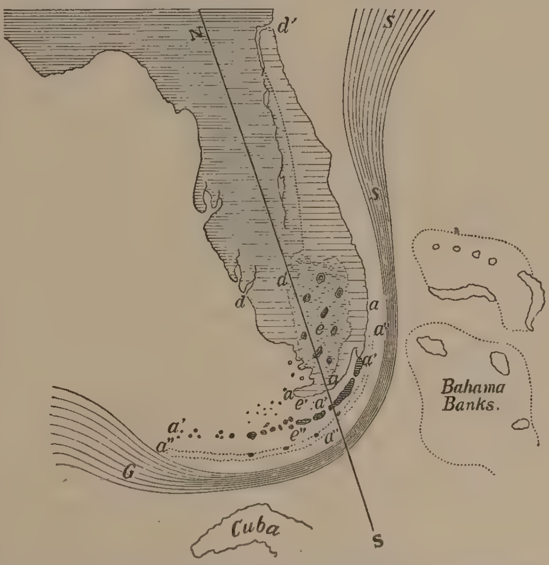

FIG. 130.—Map of Florida with its Keys and Reefs: *a*, southern coast; a', keys; a'', living reef; *e*, Everglades; e', shoal water; e'', ship-channel; *G S S*, Gulf Stream.

Reefs of Florida.

The reefs of Florida deserve a brief separate notice, both because they are different from those of the Pacific, having been formed under different conditions, and because they are much more efficient agents in *land-making*, and illustrate in a striking manner how different agencies co-operate for this purpose. The process has been accurately observed.

Description of Florida.—Fig. 130 is a *map* of Florida, with its reefs and keys, and Fig. 131 is a *section* along the line N S. The southern coast (*a a*) is ridge, elevated twelve to fifteen feet above the sea-level, within which is the Everglades (*e*) an extensive fresh-water swamp only two or three feet above sea-level, and dotted over with small islands called *hummocks*. Between the southern coast (*a a*) and the line of keys (*a′ a′*) the water (*e′*) is very shallow, only navigable to smallest fishing-craft, and dotted over with small low mangrove islands. A considerable portion of this area, in fact, forms mud-flats at low tide. Between the line of keys (*a′ a′*) and the living reef (*a″ a″*) there is a ship-channel (*e″*) five to six fathoms deep. Outside the reef (*a″ a″*) the bottom slopes rapidly into the almost unfathomable abyss of the Gulf Stream (*G S S*).

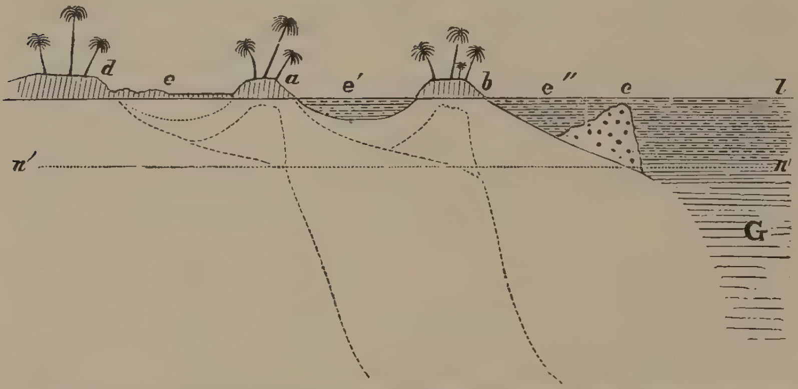

Fig. 131.—Section of same along line *N S*. Letters indicate the same. The dotted lines show supposed previous conditions.

General Process of Formation.—Now, Agassiz* has proved that not only the living reef but the keys, the southern coast, and the peninsula, certainly as far north as the north shore of the Everglades (*d d*), and probably on the east side as far north as St. Augustine (*d′*), have been formed by coral agency. The evidence of this important conclusion is that the rock in all these parts is identical with the reef-rock already described, and with what is even now forming under our eyes on the living reef (*a″ a″*). It is, moreover, almost certain that the peninsula of Florida has been progressively elongated by the formation of successive barrier reefs, one outside of the other, from the north toward the south, and the successive filling up of the intervening ship-channels, probably by coral *débris* from the reef and sediments from the mainland.

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* Coast Survey Report for 1851, p. 145 *et seq.*

History of Changes.—The history of changes was as follows: There was a time when the north shore of the Everglades (*d d*) was the southern limit of the peninsula. At that time the ridge (*a a*) which now forms the south shore was a reef. Upon this reef by the action of waves was gradually formed a line of coral islands, which finally coalesced into a continuous line of land, and by the filling up of the intervening ship-channel was added to the peninsula, the ship-channel being converted into the present Everglades. In the mean time another reef was formed in the position of the present line of keys. This has already been converted into a line of wave-formed islands, and its ship-channel into shoal water and mud-flats. Eventually the peninsula will be extended to the line of keys, and the shoal water (e') will become another Everglades and the mangrove islands its hummocks. Already another reef has been again formed outside the last, viz., the present living reef (a'' a''), and upon it the process of island-formation has commenced. This will also be eventually converted into a line of keys, into a continuous line of land, and be added in its turn to the peninsula. It is not probable that another reef will be formed outside of this, for the bottom slopes rapidly under the Gulf Stream, as seen in the section Fig. 131. In this process each reef dies when another is formed beyond it, for the water being protected by the outside reef becomes placid or lagoon water, and the strong reef-building species no longer flourish.

North of the line *d d* the evidence is of the same kind, but less complete. True reef-rock, similar to that now forming on the reef, has been found at various points as far north as St. Augustine, on the eastern shore. The western shore and interior are less known. Tuomey in 1850 traced the Eocene on the west side as far as Tampa,* and Smith in 1880 even to the north shores of the Everglades.† The heavily shaded part, therefore, gives the probable outline of the peninsula at the end of the Tertiary. If, however, as asserted by Agassiz, superficial patches of coral, of species identical with those still on the reefs, are found over this region, there must have been at least a temporary submergence during the Quaternary.

Mangrove Islands.—Mangrove-trees co-operate in an interesting manner with corals in the process of land-formation. These trees form dense jungles on the low, muddy shores of tropical regions. They are very abundant on the shores of Florida. They have the remarkable power of throwing out aërial roots from their trunks and branches, thus forming subordinate connections with the ground or with the bottom of shallow water. From these may spring other trunks, which throw out similar roots, etc. Thus an inextricable entanglement of roots and branches continues to extend far beyond the actual shore-line. These form a nidus for the detention of sediments, and protect them from the action of waves; and the shore-line thus steadily advances.

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* American Journal of Science, vol. i, p. 390, 1850.

† Ibid., vol. xxi, p. 292, 1881.

The seeds of the mangrove have also the faculty of shooting out long roots and stems, even while still attached to the parent tree. These sprouted seeds, falling into the water, float away, and if their roots touch bottom immediately fix themselves, grow into mangrove-trees, and commence multiplying in the manner described. Thus in the shoal water (*e*′) are found mangrove islands in which there is no land, but only a mangrove forest, standing above water by means of their interlaced roots. By these, however, sediments are detained, and a true island is speedily formed. It is in this way that the small mangrove islands in the shoal water on the south and west of Florida are formed. They are entirely different from the wave-formed coral islands or keys. The hummocks in the Everglades have probably a similar origin, although some of them may possibly be of coral origin.

Florida Reefs compared with other Reefs.—In comparing the reefs just described with other reefs, it will be seen that the former are unique in two respects.

1. *No other reefs continuously make land.* In fringing reefs there is a small accretion about the shore-line of the previously-existing land, but this process is quickly limited. In barriers and atolls, according to Darwin, there is always *loss* of land, only a small fraction of which is recovered by coral and wave agency. But under these agencies Florida has steadily advanced southward more than 100 miles, and the area thus added to the continent is at least 10,000 square miles. It seems utterly impossible to account for this, except by supposing some other agency at work preparing the ground for the growth of successive reefs.

Probable Agency of the Gulf Stream.—Since corals can not grow in water more than sixty to one hundred feet deep, it is evident that, unless subsidence goes on *pari passu* with the growth of the corals, a coral formation can not be more than one hundred feet thick. But there is no evidence of subsidence on the coast or keys of Florida. On the contrary, *the height of these parts is precisely the usual height of wave-formed islands, although no longer exposed to their action.* It follows, therefore, that the corals must have built upon an extensive submarine bank, produced by some other agency. Furthermore, since the reefs were formed successively one beyond another, it is evident that there must have been a progressive formation of this bank from the north toward the south. *The dotted lines* (Fig. 131) show *successive positions of the bank of the reefs.* Such a progressive extension of a bank can only be formed by sedimentary deposit. It is almost certain that in some way the Gulf Stream is connected with this sedimentary accumulation. It is to this agency, therefore, that we attribute the formation and extension of the bank upon which the corals grow.

At one time * the writer thought that the bank was formed and extended by *mechanical* sediments brought by the Gulf Stream, and deposited on the inner side of its curve; but Alexander Agassiz has shown † that the sediments are more probably *organic*, and the bank was formed partly by such sediments *brought* by the Gulf Stream from other coral banks in the Caribbean Sea, but mostly built up *in situ* by the accumulation of shells of successive generations of deep-sea animals, the Gulf Stream bringing only the conditions of rapid growth in the form of warmth and abundant food.

It is probable, therefore, that the southern portion of the peninsula of Florida is due to the co-operation of four or five different agencies, viz.: 1. The Gulf Stream building up a submarine bank to the dotted line $n' \, n'$, Fig. 131, within 100 feet of the surface; 2. Then corals building up to the surface; 3. Then waves raising it twelve to fifteen feet above the surface; 4. And, finally, *débris* from the peninsula, on the one side, and the reef and keys on the other, filling up the intervening channels, and afterward raising the level of the swamps or Everglades thus formed; 5. In this last process the mangrove-trees have assisted.

2. *The reefs of Florida are barrier reefs.* Barriers are usually supposed to indicate subsidence. The Pacific barriers, according to Darwin, commenced as fringes and became barriers by subsidence. But in Florida there has been no subsidence. They did not commence as fringes. The probable explanation is this: Corals will not grow in muddy water. On a gently-sloping shore with mud bottom, such as probably always existed on the southern shore of Florida, a fringing reef could not form, because the bottom would be always chafed by the waves and the water rendered turbid. But at a distance from shore, on the edge of the bank, where such a depth was attained that the waves no longer chafed the bottom, a barrier would form, limited on the one side by the muddiness, and on the other by the depth, of the water. Also the proximity of the Gulf Stream, carrying warmth and food, would contribute to the same result.

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* American Journal of Science, Second Series, vol. xxiii, p. 46, 1857.

† Memoirs of the American Academy of Science, vol. xi, p. 107.

It will be observed that this view of the formation of barriers differs from both that of Darwin and that of Murray. It has been adopted by Captain Guppy for some of the barriers of the Pacific.*

Shell-Deposits.

Rivers carry carbonate of lime in solution to the sea (p. 83). In some bays, where large quantities of this material are carried by rivers running through limestone countries, the excess may be deposited as a *chemical* deposit. But in most cases sea-water contains less lime-carbonate than river-water. The reason is, that the lime-carbonate in sea-water is continually being drafted upon by organisms and deposited on their death as organic limestones. We have already shown how coral limestone is thus formed. But there are many other limestone-forming animals, and some species form other kinds of deposits besides limestone.

Molluscous Shells.—*Shallow-water deposits* of this kind are made principally by mollusca which, living in immense numbers near shore and on submarine banks, leave their dead shells generation after generation, and thus form sometimes pure shelly deposits, and sometimes shells mingled with sediments due to other agencies. On quiet shores the shells are quite perfect, whether imbedded in mud or forming shell-banks like our oyster banks ; but when exposed to the action of breakers, they are broken into coarse fragments, or even comminuted, worn into rounded granules, and cemented into shell-rock or oölitic rock. Such shell-rock and oölitic rock are now being formed on the coast of the Florida keys and of the West Indies. Similar rock is found in every part of the world in the interior of continents. They indicate the existence in these places of a shore-line or of shallow water in some previous geological epoch.

Microscopic Shells.—Microscopic plants and animals are known to multiply in numbers with almost incredible rapidity. Many of them form no shell, and therefore are of no geological importance; but many species form shells of silica or of carbonate of lime, and these of course accumulate generation after generation, until important deposits are formed.

Fresh-water Deposits.—In streams, ponds, lakes, and hot springs, the beautiful siliceous shells of diatoms (uni-celled plants) accumulate without limit. The ooze at the bottom of clear ponds, or lakes, as, for example, in the deepest parts of Lake Tahoe, consists often wholly of these shells. Diatoms live also in great numbers in the hot springs of California, Nevada, and Yellowstone Park, and the deposits of such springs sometimes consist wholly of these shells, and in Yellowstone Park cover many square miles, and are five to six feet thick.* Thick strata, belonging to earlier geological times, are found wholly composed of diatoms. We are thus able to explain the formation of these strata.

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* Nature, vol. xxxv, p. 77, 1886.

Deep-sea Deposits.—Over nearly all the bottom of deep seas, beyond the reach of sedimentary deposits, we find a white, sticky ooze, composed of the carbonate-of-lime shells of microscopic animals (foraminifers), Fig. 132, and microscopic plants (coccospheres). Some of these seem to be *living*, or recently dead; some dead and empty, but still perfect; but most of them completely disintegrated. On account of the great abundance of the shells of one form of foraminifera, this soft, white mud is called *globigerina ooze.* Mingled in considerable numbers among the calcareous shells are others of silica. These are also partly animals (radiolaria) and partly plants (diatoms). The extraordinary resemblance of this deep-sea ooze, both in chemical and microscopic character, to chalk, leaves no room for doubt that chalk was formed in this way.

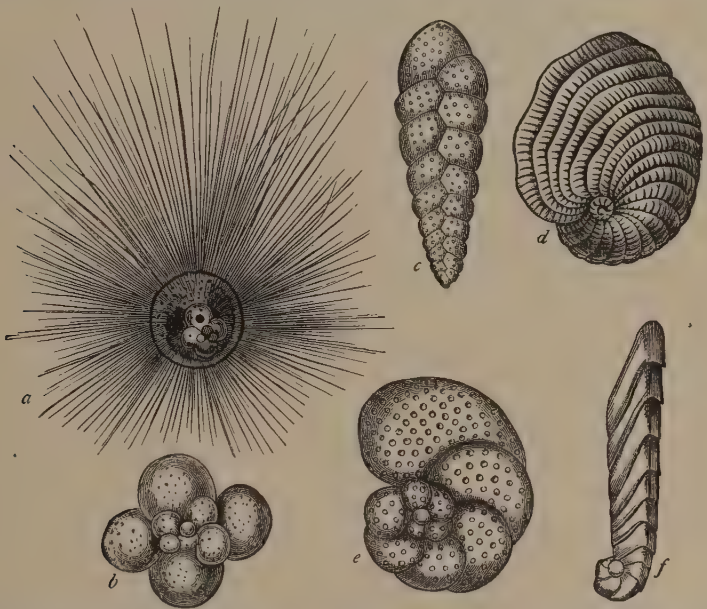

FIG. 132.—Shells of Living *Foraminifera*: *a*, *Orbulina universa*, in its perfect condition, showing the tubular spines which radiate from the surface of the shell; *b*, *Globigerina bulloides*, in its ordinary condition, the thin hollow spines which are attached to the shell when perfect having been broken off; *c*, *Textularia variabilis*; *d*, *Peneroplis planatus*; *e*, *Rotalia concamerata*; *f*, *Cristellaria subarcuatula*. Fig. *a* is after Wyville Thomson; the others are after Williamson. All the figures are greatly enlarged (after Nicholson).

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* Weed, Botanical Gazette, May, 1889.

PART II.

STRUCTURAL GEOLOGY.

We have thus far studied *causes now in operation* or dynamical principles. We now study the *structure of the earth* (which is the effect of the same accumulated throughout all geological time), and the *application of the foregoing principles* in its explanation. The subject of this part, therefore, is both *structural and dynamical* geology.

CHAPTER I.

GENERAL FORM AND STRUCTURE OF THE EARTH.

1. *Form of the Earth.*

The general form of the earth is that of an oblate spheroid flattened at the poles, or, more definitely, an ellipsoid of revolution on the minor axis. The polar diameter is less than the equatorial diameter by about twenty-six miles, or about $\frac{1}{300}$ of the mean diameter.* The highest mountains, being only five miles high, do not interfere greatly with the general form.

This form, being precisely that which a fluid body revolving freely would assume, has been regarded by many of the most distinguished physicists as conclusive evidence of the former fluid condition of the earth. The argument may be stated as follows: 1. A fluid body standing still, under the influence only of its own molecular or gravitating forces, would assume a perfectly spherical form; but, if rotating, the form which it would assume, as the only form of equilibrium, is that of an oblate spheroid, with its shortest diameter coincident with the axis of rotation. Now, this is precisely the form not only of the earth, but, as far as known, of all the planetary bodies. 2. In an oblate spheroid of rotation the oblateness increases with the rapidity of rotation. Now, Jupiter, which turns on its axis in ten hours, is much more oblate than the earth. The flattening of the earth is only about $\frac{1}{300}$ of its diameter, while that of Jupiter is about $\frac{1}{16}$. 3. The forms of the earth and of Jupiter have been calculated; the data of calculation being the former fluidity, the time of rotation and an assumed rate of increasing density from surface to center; and the calculated form comes out nearly the same as the measured form.

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* **More exactly $\frac{1}{293\cdot5}$, Philosophical Magazine, vol. x, p. 121, 1880.**

The force of this argument, however, has been, to say the least, greatly exaggerated. The oblateness of the earth and planets, as has been shown by Playfair and Herschel,[*] only proves that they have assumed their form under the influence of rotation—that they are spheroids of rotation—but not that they have ever been in a fluid condition. For since a rotating body, whatever be its form, always *tends* to assume an oblate spheroid form, and since the materials on the surface of the earth are in continual motion, being shifted hither and thither under the influence of atmospheric and aqueous agencies, it is evident that the final and total result of such motions must be in the course of infinite ages to bring the earth to the only form of equilibrium of a rotating body, viz., an oblate spheroid. If, for example, the earth were a rigid sphere, standing still and covered with water, and then set rotating, the waters would gather into an equatorial ocean, and the land be left as polar continents. But this condition would not remain; for atmospheric and aqueous agencies, if unopposed, would eventually cut down the polar continents and deposit them as sediments in the equatorial seas, and the solid earth or *lithosphere* would thus become an oblate spheroid. This final effect of degrading agencies would not be opposed by igneous agencies, as the action of these is irregular, and does not tend to any particular form of the earth. Yet this applies only to the *general* spheroidal form; for Hennessey has shown[†] that although the spheroidal form would be assumed either by fluidity or by abrasion, yet the *degree* of ellipticity of the spheroid would be different, and probably sensibly different in two cases, being greater in the former; and that the actual form of the earth more nearly approaches this greater degree.

Therefore, although there are many reasons, drawn both from geology and from the nebular hypothesis, for believing that the earth was once in an incandescent fluid condition, and that it then assumed an oblate spheroid form in obedience to the laws of equilibrium of fluids; yet this form alone must not be assumed as demonstrative proof of such original condition, since a similar form would be produced by causes now in operation on the earth-surface, whatever may have been its original form and condition. Moreover, it is evident that the exact original form, however determined, can not have been retained; for there are causes in operation which have tended constantly to modify it. If abrasion can produce, it can also modify the form of the earth. If the form of the earth is a form of equilibrium, then a change in the *rate* of rotation will produce a change in the *degree* of oblateness or ellipticity. Now, when the earth first solidified from an incandescent liquid condition, it had a certain degree of ellipticity determined by its rate of rotation; but this rate of rotation has not been constant. The earth, from that time until now, has been cooling and contracting; and contraction would tend to accelerate rotation and *increase* ellipticity. But, also, ever since an ocean was first formed by precipitation on the cooling earth, tides have been formed by the moon and sun, and the *friction of the dragging tides* would tend to retard rotation and *decrease* ellipticity. At first, doubtless, the contractional acceleration prevailed and ellipticity increased; but now tidal retardation prevails, and ellipticity is probably decreasing.

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[*] Lyell, Principles of Geology, vol. ii, p. 199.

[†] Philosophical Magazine, vol. vii, p. 67, 1879, vol. x, p. 119, 1880, and vol. xi, p. 283, 1881.

2. *Density of the Earth.*

The mean density of the earth, as determined by several independent methods, is about 5·6. The density of the materials of the earth-surface, leaving out water, is only about 2·5. It is evident, therefore, that the density of the central portions must be much more than 5·6. This great interior density may be the result—1. *Of a difference of material.* It is not improbable that the surface of the earth has become oxidized by contact with the atmosphere, and that at great depths the earth may consist largely of metallic masses. Or the great interior density may be the result.—2. Of condensation by the immense pressure of the superincumbent mass. In either case the tendency of *increasing heat* would be to diminish the increasing density. But how much of the greater density is due to difference of material, and how much to increasing pressure, and how much these are counterbalanced by expansion due to increasing heat, it is impossible to determine.

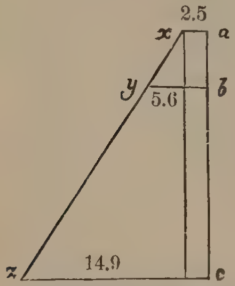

FIG. 133.—Diagram illustrating the Increasing Density of the Earth.

The increase of density has been somewhat arbitrarily assumed to follow an arithmetical law. Under this condition a density equal to the mean density would be found at $\frac{1}{4}$ radius from the surface, and taking the surface density at 2·5, and the mean density at 5·6, the *central* density would be nearly 15. In the diagram (Fig. 133), if $a\,c =$

radius, the ordinate $a\,x$ = surface density = 2·5, and $b\,y$ = mean density = 5·6, then $c\,z$, the central density, will be = 14·9.

It is needless to say that this result (Plana's) is unreliable.

3. *The Crust of the Earth.*

The surface of the earth undoubtedly differs greatly in many respects from its interior, and therefore the exterior portion may very properly be termed a *crust*. It is a *cool* crust, covering an *incandescent* interior; a *stratified* crust, covering an *unstratified* interior; probably an *oxidized* crust, covering an *unoxidized* interior; and many suppose a *solid* crust, covering a *liquid* interior. This last idea, although very doubtful (p. 86), has probably given rise to the term *crust*. The term, however, is used by all geologists, without reference to any theory of interior condition, and only to express that portion of the exterior which is subject to human observation. The thickness which is exposed to inspection is about ten to twenty miles.

Means of Geological Observation.—The means by which we are enabled to inspect the earth below its immediate surface are: 1. *Artificial sections*, such as mines, artesian wells, etc. These, however, penetrate only to the insignificant depth of half a mile, or rarely of a mile (p. 76). 2. *Natural sections*, such as cliffs, ravines, cañons, etc. These, as we have already seen (p. 17), sometimes penetrate 5,000 to 6,000 feet. 3. Folding, and subsequent erosion of the crust, by which strata from great depths have their edges exposed. Thus, in passing along the surface from *s* to *a* (Fig. 134), lower and lower rocks are successively brought under inspection. The dotted lines show how much has been cut away, and therefore the depth of strata exposed. In this way often ten miles depth of strata are brought into view. This is by far the most important means of observation; without it the study of geology would be almost impossible. 4. Volcanoes bring up to the surface materials from unknown but probably very great depths.

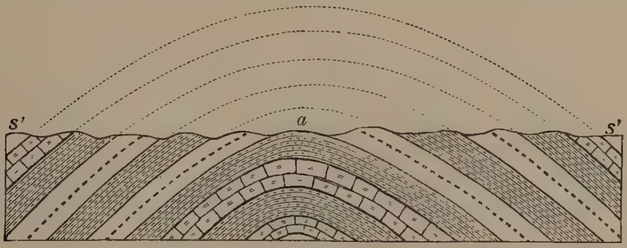

Fig. 134.

Ten miles seems an insignificant fraction of the earth's radius, being in fact equivalent to less than one thirtieth of an inch in a globe two feet in diameter. It may seem at first sight an insufficient basis for a science of the earth. We must recollect, however, that only this crust has been inhabited by animals and plants—on this crust only have operated atmospheric, aqueous, and organic agencies—and therefore on this insignificant crust have been recorded all the most important events in the history of the earth.

4. *General Surface Configuration of the Earth.*

The surface inequalities of the solid earth or lithosphere are of two general kinds, which may be called *greater* and *lesser*. The one is due to *interior*, the other to *exterior* causes; the one to *igneous*, the other to *aqueous* or erosive agencies. The lesser inequalities we will treat under the head of forms of sculpture (p. 278). Our discussion now is limited to the greater. Again, these are of two orders of greatness, viz., those which constitute *land-masses and ocean basins*, and those which constitute *mountain-ranges* and intervening valleys. These latter we shall treat fully hereafter (p. 260); we are therefore specially concerned now with *the former*.

Nearly three quarters of the whole surface of the earth is covered by the ocean.* The mean height of the continents, according to the most recent results, is as follows: Europe, 984 feet; Asia and Africa, 1,640 feet; America, North and South, 1,083 feet; Australia, 820 feet. The mean height of all land is given as about 1,378 feet.† These figures are considerably greater than those given by Humboldt and heretofore adopted.

The mean depth of the ocean is probably 12,000 to 15,000 feet (Thompson). There is probably water enough in the ocean, if the inequalities of the earth's surface were removed, to cover the earth to a depth of about two miles.

The extreme height of the land above the sea-level is five miles, and the extreme depth of the ocean is at least as much. The extreme relief of the lithosphere is therefore not less than ten miles.

Cause of Land-Surfaces and Sea-Bottoms.—The most usual idea among geologists as to the general constitution of the earth is that the earth is still essentially a liquid mass, covered by a solid shell of twenty-five to thirty miles in thickness; and that the great inequalities, constituting land-surfaces and ocean-bottoms, are produced by the upbending and down-bending of this crust into convex and concave arches, as shown in Fig. 135. The clear statement of this view is sufficient to refute it; for, when it is remembered that the arches with which we are here dealing have a span of nearly a semi-circumference of the earth, it becomes evident that no such arch, either above or below the mean level, could sustain itself for a moment: for the pressure would be thirty times the crushing strength of steel and 500 times the crushing strength of granite.* The only condition under which such inequalities could sustain themselves on a supporting liquid is the existence of inequalities on the under surface of the crust next the liquid, similar to those on the upper surface, but in reverse, as shown in Fig. 136. And these lower or under-surface inequalities would have to be repeated not only for the largest inequalities, viz., continental surfaces and ocean-bottoms, but also for great mountain plateaus. And thus the hypothesis seems to break down with the weight of its own assumption.†

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* Land : water :: 1 : 2·63 (Wagner, 1895).

† Krümmel, American Naturalist, vol. xiii, p. 464, 1879. More recent estimates make it a little over 2,000 feet.—Jour. Geol., vol. i, p. 422, 1893.

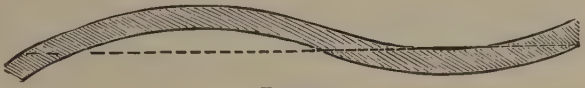

FIG. 135.

Besides, we have already given good reasons (pages 87 and 88) for believing that the earth is substantially solid. Upon the hypothesis of a substantially solid earth, we explain the great inequalities constituting continental surfaces and ocean-bottoms by *unequal radial contraction* of the earth in its secular cooling.

The earth was undoubtedly at one time an incandescent liquid globe. It then, as we believe, cooled to a *substantial* solid, although probably with a sub-crust layer underlying large areas of the solid crust, and separating it from the solid nucleus. When first solidified the earth was doubtless a regular *oblate spheroid*, and, when sufficiently cool to allow condensation of aqueous vapor, covered with a *universal ocean.* By continued cooling it gradually contracted, and if the rate of cooling and contraction had been equal in all parts of the surface it would have retained its regular spheroid form. But, without perfect homogeneity of composition and equality of conductivity and of coefficient of contraction in all parts (which is extremely improbable), such equality of cooling and contraction would be impossible. Some parts, therefore, cooled and contracted *toward the center* more rapidly than others. These more rapidly contracting areas would form hollows and the less rap-

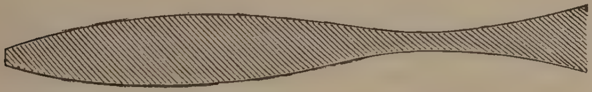

FIG. 136.—Diagram illustrating the Conditions of Equilibrium of a Solid Crust on a Liquid Interior.

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* Woodward, Science, 1, 194, 1895.

† It has been shown by G. H. Darwin that the great inequalities of the earth's surface could not be sustained unless the earth be as rigid as granite for a depth of 1,000 miles. —Proceeding of the Royal Society, June, 1881.

idly contracting areas protuberances. The waters would be gathered in the hollows and form oceans, while the protuberances would become continents. In other words, oceanic basin and land-masses are the result of *slight distortion of the regular spheroid* by *unequal radial contraction.* This is evidently a *true* cause; and, when we consider the smallness of these inequalities in comparison with the size of the earth, it will seem a *sufficient* cause. The mean inequality of the kind we are now considering is about two and a half miles. This in a globe of two feet in diameter would be less than one one-hundredth of an inch—an amount that would be scarcely perceptible. If a globe of clay or of stone of this size were heated to incandescence and *in this condition* ground to a true sphere and then allowed to cool, it is probable that the inequality would be as great as or greater than the above.*

It is only the greatest inequalities, viz., land-surfaces and sea-bottoms, which we account for in this way. Mountain-chains are certainly formed by a different process, which we will discuss under that head (p. 260); and it is even possible, though not probable, that the causes which operate to produce mountain-chains may also produce these greatest inequalities.

The continuance of these causes would tend constantly to increase the extent and height of the land, and to increase the depth, but diminish the extent of the sea. This, on the whole, seems to have been the fact, during the history of the earth, as will be shown in Part III. Nevertheless, local causes, both aqueous and igneous, as already shown in Part I, have greatly modified the general contour, both map and profile, given by secular contraction.

Sub-ocean Crust is denser.—Or, again: the same result would follow even if there were no difference of conductivity, but only of density over large areas. For in so large a globe as the earth—unless preternaturally rigid—such large areas must be in a state of hydrostatic equilibrium (Isostasy). The denser areas must sink and form the ocean-bottoms and the lighter areas rise into continental surfaces. But since denser areas are also probably more conductive, and therefore cool faster, it is evident that the two causes would co-operate. The conclusion, therefore, is inevitable that ocean-bottoms are lower because, and in proportion as, the sub-ocean matter is denser, and continents are higher because, and in proportion as, the sub-continent matter is lighter.

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* To this, according to Faye (Comptes Rendus, vol. xc, p. 1185, 1880), must be added still another cause. As soon as the water collects in the depressions formed by unequal radial contraction, its very presence would tend to increase the cooling and contracting of these parts, and thus to deepen still further the depressions. This effect results (1) from the more rapid cooling of water by convection, and (2) from the circulation of ice-cold water from the poles along the sea bottom (pp. 40 and 41).

Most careful recent gravity determinations across the American Continent have confirmed these views.*

Laws of Continental Form.—That the general contour of continents and sea-bottoms has been determined by some general cause, such as secular contraction, affecting the whole earth, is further shown by the laws of continental form. The most important of these are as follows:

1. Continents consist of a great interior basin, bordered by elevated coast-chain rims. This typical form is most conspicuously seen in North and South America, Africa, and Australia. Europe-Asia is more irregular, and therefore the typical form is less distinct. We give in Fig. 137, *A* and *B*, an east-and-west section of North America and of Australia, as typical examples of continental structure.

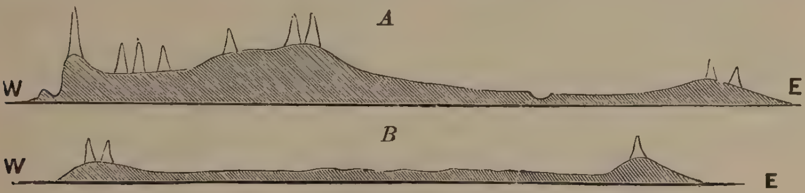

Fig. 137.—*A*, section across North America; *B*, section across Australia (after Guyot).

The great rivers of the world, e. g., the Nile, Mississippi, Amazon, La Plata, etc., drain these interior continental basins.

2. In each continent the greatest range of mountains faces the greatest ocean. Thus in America the greatest range is on the west, facing the Pacific; while in Africa the greatest range is on the east, facing the Indian Ocean. In Asia the Himalayas face the Indian Ocean, while the Altai face the Polar Sea. In Australia the greatest range is to the east, facing the Pacific.

3. The greatest ranges have been subjected to the greatest and most complex foldings of the strata, and are the seats of the greatest metamorphism (p. 230) and the greatest volcanic activity.

4. The outlines of the present continents have been sketched in the earliest geological times, and have been gradually developed and perfected in the course of the history of the earth. In the case of the North American Continent this will be shown in Part III.

The cause of some of these laws will be discussed under the head of Mountain-Chains.

Rocks.

In geology the term *rock* is used to signify any material constituting a portion of the earth, whether hard or soft. Thus, a bed of sand or clay is no less a rock than the hardest granite. In fact, it is impossible to draw any scientific distinction between materials founded upon hardness alone. The same mass of limestone may be soft chalk in one part and hard marble in another: the same bed of clay may be hard slate in one part and good brick-earth in another; the same bed of sandstone may be hard gritstone in one part and soft enough to be spaded in another. The same volcanic material may be stony, glassy, scoriaceous, or loose sand or ashes.

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* Putnam and Gilbert, Bull. Phil. Soc., Wash., No. 13, p. 31, 1895.

Classes of Rocks.—All rocks are divided into two great classes, viz., *stratified rocks* and *unstratified rocks.* Stratified rocks are more or less consolidated sediments, and are usually, therefore, more or less *earthy* in structure and of *aqueous origin.* Unstratified rocks have been more or less completely fused, and therefore are *crystalline* in structure and of *igneous origin.*

CHAPTER II.

STRATIFIED OR SEDIMENTARY ROCKS.

Section 1.—Kinds, Structure, and Position.

Stratification.—Stratified rocks are characterized by the fact that they are separated by parallel division-planes into larger sheet-like masses called *strata*, and these into smaller *layers* or *beds*, and these again into still smaller *laminæ.* These terms are purely relative, and are therefore somewhat loosely used. Usually, however, the term *stratum* refers to the mineralogical character; the term *layer* to subdivisions of a stratum distinguishable by difference of color or fineness; and the term *lamina* to those smallest subdivisions, evidently produced by the sorting power of water. For instance, in the annexed figure we have three strata of sandstone, clay, and limestone, each divisible into two layers differing in fineness or compactness of the material, and all finely laminated by the sorting power of water. The lamination, however, is not represented, except in the clay stratum, *sh.* There is another structure represented in the figure—viz., the cross

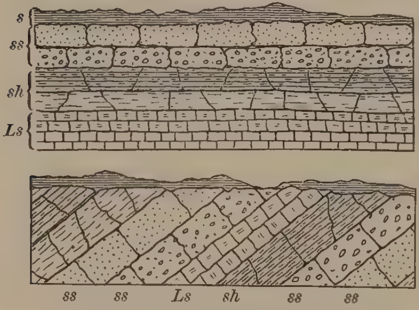

Fig. 138.—Sections of Horizontal and Inclined Strata: *s*, soil; *ss*, sandstone; *sh*, shale; *Ls*, limestone.

fractures or joints. These, however, are not peculiar to stratified rocks, and will be discussed at another time.

Extent and Thickness.—Probably nine-tenths of the surface of the land, and, of course, the whole of the sea-bottom, are covered with stratified rocks. Even where these are wanting it is because they have been removed by erosion or else covered up and concealed by fused matter outpoured on the surface. This proves that every portion of the surface of the earth has been at some time covered with water. The extreme thickness of stratified rocks is certainly not less than twenty miles; the average thickness is probably several miles.

Kinds of Stratified Rocks.—Stratified rocks are of three kinds, and their mixtures, viz., *arenaceous* or sand rocks, *argillaceous* or clay rocks, and *calcareous* or lime rocks. Arenaceous rocks, in their incoherent state, are *sand*, *gravel*, *shingle*, *rubble*, etc., and in their compacted state and *sandstones*, *gritstones*, *conglomerates*, and *breccias*. Conglomerates are composed of *rounded* pebbles, and breccias of *angular* fragments cemented together. Argillaceous rocks, in their incoherent states, are *muds* and *clays;* partially consolidated and finely laminated they form *shales*, and thoroughly consolidated they form *slates.* Calcareous rocks are *chalk*, *limestone*, and *marble.* They are seldom in an incoherent state, except as *chalk.*

These different kinds of rocks graduate into each other through intermediate shades. Thus we may have *argillaceous sandstones*, *calcareous sandstones*, and *calcareous shales* or marls.

The most important points connected with stratified rocks we will now, for the sake of greater clearness, bring out in the form of distinct propositions. On these propositions is based nearly the whole of geological reasoning.

I. Stratified Rocks are more or less Consolidated Sediments.—The evidence of this fundamental proposition is abundant and conclusive. 1. Beds of mud; clay, or sand, as already stated, may often be traced by insensible gradations into shales and sandstones. 2. In many places the process of consolidation is now going on before our eyes. This is most conspicuous in sediments deposited at the mouths of large rivers whose waters contain abundance of carbonate of lime in solution, or on the coasts of seas containing much carbonate of lime. Thus the sediments of the Rhine are now consolidating into hard stone (p. 84), and on the coasts of Florida, Cuba, and on coral coasts generally, comminuted shells and corals are quickly cemented into solid rock (p. 163). 3. All kinds of lamination produced by the sorting power of water which has been observed in sediments, have also been observed in stratified rocks. 4. Stratified rocks contain the remains of animals and plants, precisely as the stratified mud of our present rivers contains river-shells, our present beaches sea-shells, or the mud of our swamps the bones of our higher animals drifted from the high lands. 5. Impressions of various kinds, such as ripple-marks, rain-prints, footprints, etc., evidently formed when the rock was in the condition of soft mud, complete the proof. It may be considered as absolutely certain that *stratified rocks are sediments.* Arenacious and argillaceous rocks are the *débris* of eroded land, and are therefore called *mechanical* sediments or *fragmental* rocks. Limestones are either chemical deposits in lakes and seas, or are the comminuted remains of organisms. They are therefore either chemical or organic sediments. Conglomerates, grits, and sandstones, indicate violent action; shales and clays quiet action in sheltered spots. Limestones are sometimes produced by violent action—e. g., coral breccia—sometimes very quiet action, as in deep-sea deposits.

We have already seen (p. 4) that rocks under atmospheric agencies are disintegrated into soils, and these soils are carried by rivers and deposited as sediments in lakes and seas. Now we see that these sediments are again in the course of time consolidated into rocks, to be again raised by igneous agencies into land, and again disintegrated into soils, and redeposited as sediments. Thus the same material has been in some cases worked over many times in an ever-recurring cycle. This is another illustration of the great law of circulation, so universal in Nature.

Cause of Consolidation.—The consolidation of sediments into rocks in many cases is due to some *cementing principle*, such as carbonate of lime, silica, or oxide of iron, present in percolating waters. In such cases the consolidation often takes place rapidly. In other cases it is due to *long-continued heavy pressure*, and in still others to *long-continued*, though not necessarily very great, *elevation of temperature* in presence of water. In these cases the process is very slow, and therefore it has not progressed greatly in the more recent rocks.

II. Stratified Rocks have been gradually deposited.—The following facts show that in many cases rocks have been deposited with extreme slowness: 1. Shales are often found the lamination of which is beautifully distinct and yet each lamina no thicker than cardboard. Now, each lamina was separately formed by alternating conditions, such as the rise and fall of tide, or the flood and fall of river. 2. Again, on the *interior* of imbedded shells of mollusca, or on the outer surface of the shells of sea-urchins *deprived of their spines*, are often found attached other shells, as shown in the following figures. Now, these shells must have been dead, *but not yet covered with deposit* during the whole time the attached shell was growing. As a general rule, in fragmental rocks the finest materials, such as clay and mud, have been deposited very slowly, while coarse materials, such as sand, gravel, and pebbles, have been deposited rapidly. Limestones, being generally formed by the accumulation of the calcareous remains of successive generations of organisms, living and dying on the same spot, must have accumulated with extreme slowness. The same is true of infusorial earths.

It is necessary, therefore, to bear in mind that all stratified rocks were formed in previous epochs by the *regular* operation of agents similar to those in operation at present, and not by irregular or cataclysmic action, as supposed by the older geologists. Thus, *cæteris paribus*, the thickness of a rock may be taken as a rude measure of the time consumed in its formation.

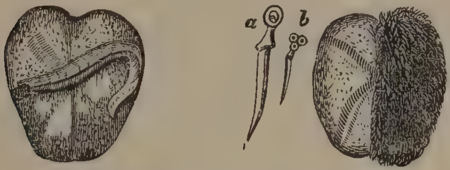

FIG. 139.—Serpula on Shell of an Echinoderm.

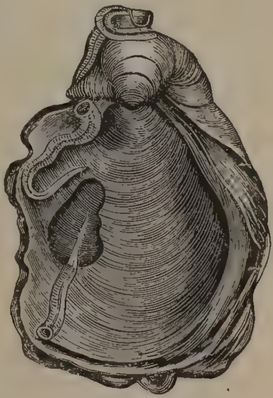

FIG. 140 —Serpulæ on Interior of a Shell.

III. Stratified Rocks were originally nearly horizontal.—The horizontal position is naturally assumed by all sediments in obedience to the law of gravity. When, therefore, we find strata highly inclined or folded, we conclude that their position has been subsequently changed. It must not be supposed, however, that the planes which separate strata were originally perfectly horizontal, or that the strata themselves were of unvarying thickness, and laid atop of each other like the sheets of a ream of paper. On the contrary, each stratum, when first deposited, must be regarded as a widely-expanded *cake*, thickest in the middle and thinning out at the edges, and interlapping there with other similar cakes. Fig. 141 is a diagram showing the mode of interlapping.

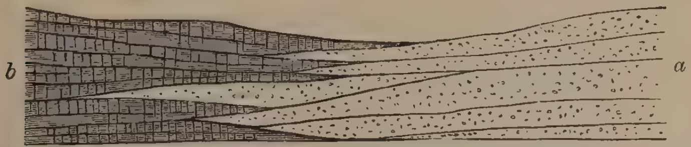

FIG. 141.—Diagram showing Thinning out of Beds: *a*, sandstones and conglomerates; *b*, limestones.

The extent of these cakes depends upon the nature of the material. In fine materials strata assume the form of extensive thin sheets, while coarse materials thin out more rapidly, and are therefore more local.

The most important apparent exception to the law of original horizontality is the phenomenon of *oblique lamination* or cross bedding.

This kind of lamination is formed by rapid, shifting currents, bearing abundance of coarse materials, or by chafing of waves on an exposed beach. Many examples of similar lamination are found in rocks of previous epochs. Figs. 142 and 143 represent such examples. In some cases cross bedding may be mistaken for highly-inclined strata; careful examination, however, will show that the strata are not parallel with the laminæ. The strata were originally (and in the cases represented in the figures are *still*) horizontal, while the laminæ are oblique.

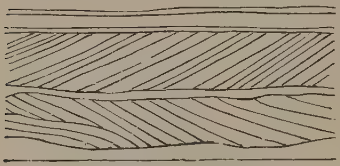

FIG. 142.—Oblique Lamination or cross bedding.

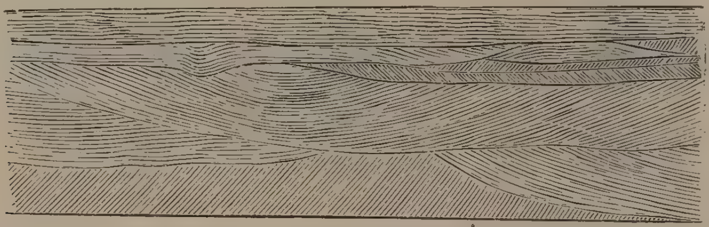

FIG. 143.—Section on Mississippi Central Railroad at Oxford (after Hilgard): Oblique lamination.

Elevated, Inclined, and Folded Strata.—We may assume with confidence that stratified rocks were deposited as *sediments* at the *bottom of water* and in a horizontal or nearly *horizontal position.* But we do not now find them usually in this condition, place, or position. Some-

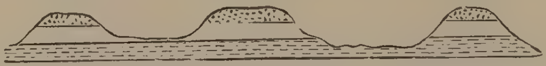

FIG. 144.

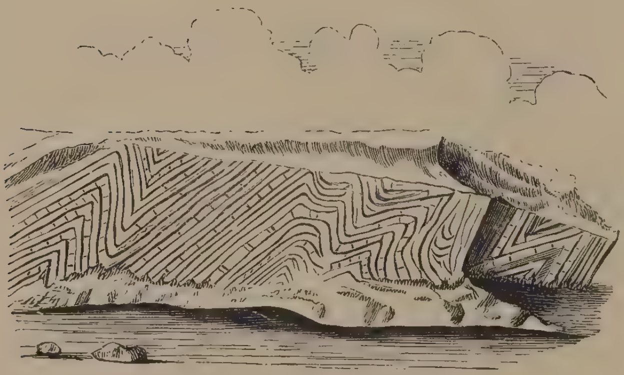

FIG. 145.—Contorted Strata.

times, indeed, they are still soft, but usually stony; sometimes in the vicinity of water, but oftener far in the interior of continents and high up the slopes of mountains; sometimes they are still *horizontal* though elevated (Fig. 144); but often, especially in mountain-regions, we find them tilted at all angles, folded, contorted (Fig. 145), overturned, broken, and slipped, so that it is difficult sometimes to determine their original order of superposition. Again, in folded strata, sometimes we have the most intricate crumplings of the finer *laminæ*, such as may be seen in a hand specimen (Fig. 146). Sometimes whole groups of strata are thus folded, as can be seen at one view on a sea-cliff or cañon wall

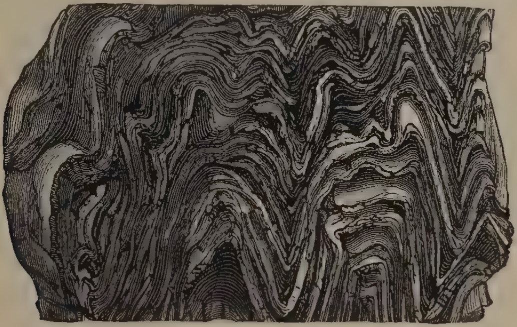

Fig. 146.—Crumpled Laminæ (after Geikie).

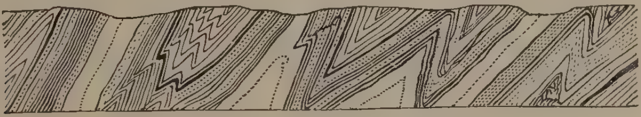

Fig. 147.—Contorted Strata (from Logan).

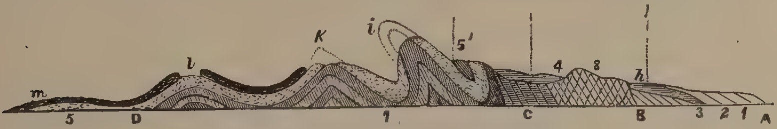

Fig. 148.—Section of Appalachian Chain.

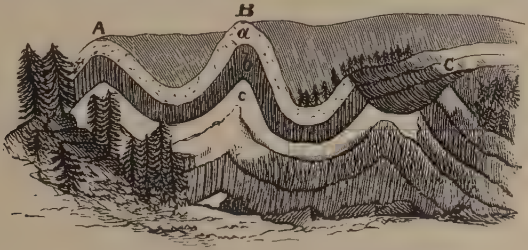

Fig. 149.—Section of the Jura Mountains.

(Fig. 147). Sometimes the whole crust of the earth, for miles in thickness and many miles in extent, are thrown into great crust-waves constituting mountain-ranges with their intervening valleys (Figs. 148 and 149). In such cases the folded structure is not visible at one view, but only brought out by extended survey. In cases of strong folding the strata are often broken and dislocated (Figs. 200–207). In all cases of elevated strata, whether level or tilted and folded, large portions of the upper parts are carried away by erosion and the remainder is left in isolated patches and basins, or else standing at all angles, with their edges exposed (Figs. 147, 148, and in all the other figures under this head). Such exposure on the surface of the edges of eroded strata is called an *outcrop*.

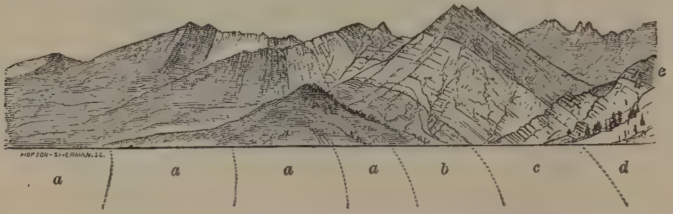

FIG. 150.—Upturned and Eroded Strata, Elk Mountains, Colorado (after Hayden).

Definition of Terms.—There are certain terms in frequent use by geologists which must now be defined. These are *dip and strike*, *anticline and syncline* and *conformity and unconformity*.

Dip and Strike.—The dip of strata is their inclination to a horizontal plane. There are always two elements to be considered—viz., *direction* and *amount*. Thus in Fig. 151 the strata dip southward about 30°. The angle of dip is measured by a clinometer (Fig. 152), and the direction of dip by a compass. These two are often conveniently united in one instrument. As thus determined the angle of dip varies from 0° to 90°, or from horizontality to verticality. Fig. 153 is an example of vertical strata. In strongly folded rocks the strata may be pushed beyond the perpendicular (Fig 154), or even completely reversed (Fig. 209 *C*), so that the change from the original position may be nearly or quite 180°.

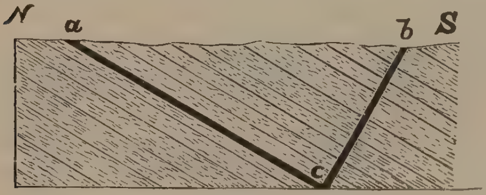

FIG. 151.

In a series of regularly dipping strata, like that of Fig. 151, it is easy to estimate the thickness of the series. The thickness, $b\ c$, = distance $a\ b \times$ sin. of the angle of dip 30°. We sometimes find an *actual* section such as that represented in the figure, but more usually we observe the successive outcrops on the surface and the angle of dip, and construct an *ideal* section. This is easy enough if the rocks are bare, but if covered with soil, we must take advantage of every bare spot, of every ravine, gully, and stream-bed where the rocks may be exposed, of every quarry, railroad-cutting, well, etc., and put these together in the attempt to make a map of outcrop and a section.

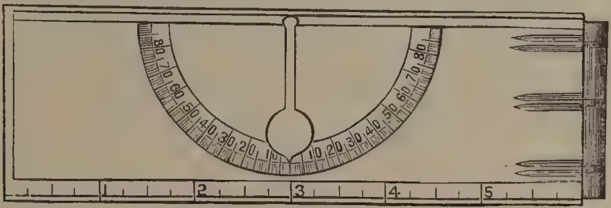

Fig. 152.—Clinometer.

The *strike* of strata is the *direction of their trend*, or, more accurately, is *the line of intersection of the strata with a horizontal plane.* It is always at right angles to the line of dip. If the dip is north or south, the strike is east and west. If the strata are plane, the strike is a straight line; but if they are bent, the strike may be a curve. For example, if the strata are lifted up in the form of a cone or a dome, the strike will be circular; if the strata be folded and then tilted in a direction at right angles to the folding force, the strike will be sinuous. Again, if the surface of the ground is level, the *outcrop* will be the strike and will be straight or sinuous, according as the strike is one or the other. But the outcrop is usually far more irregular than the strike, as it is affected also by irregularities of surface produced by erosion; so that in a broken country the outcrop of folded strata is extremely complex.

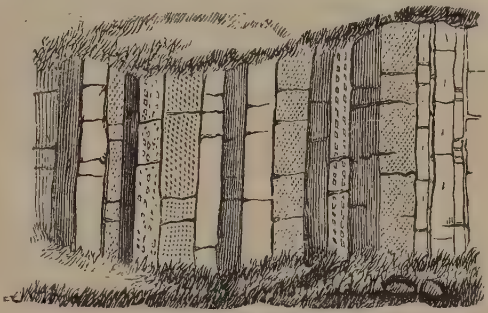
Fig. 153.—Vertical Strata.

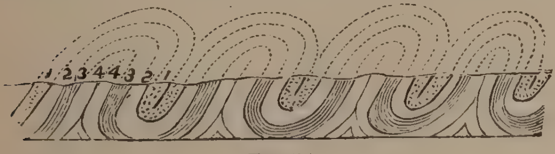

Fig. 154.

Anticline and Syncline.—Strata are usually more or less folded, and therefore form alternate saddles and troughs. The saddles are *anticlines*, the troughs *synclines*. The line along the top of the saddle is an *anticlinal axis*, the line along the bottom of the trough a *synclinal axis*. If it were not for erosion, the anticlines would be ridges and the synclines valleys. If erosion cuts down to nearly a plane, as in Fig. 155, then an anticline is known by the strata being repeated on each side of an axis and dipping *away* from one another; a syncline by the strata also repeated on each side of an axis but dipping *toward* one another. In the one case the *oldest and lowest* strata are on the axis and they become higher and newer as we go either way; in the other the *uppermost and newest* strata are along the axis, and they become lower and older as we go either way.

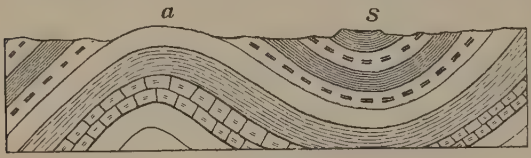

Fig. 155.

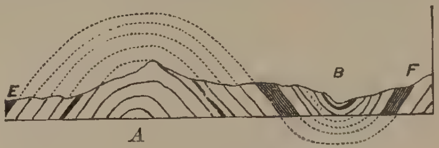

Fig. 156.—Section of Undulating Strata.

But erosion usually forms ridges and valleys. In this case sometimes the ridges are anticlines and the valleys synclines, as in Fig. 156, but sometimes the reverse is true. It is very common to have synclinal ridges and anticlinal valleys (Fig. 157). In this case the original configuration is completely reversed by erosion. This will be explained in another chapter (p. 280).

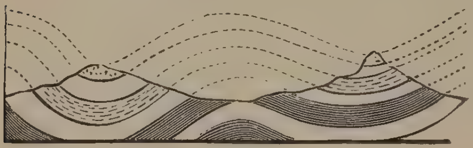

Fig. 157.

Fig. 156 and the following figures (158 and 159) will illustrate some of these points. Suppose we have strata gently folded, so as to make an anticline and syncline, and then the whole tilted and finally eroded down to a nearly level surface. The map of the outcrop of such a series is shown in Fig. 158, in which A A′ is an anticline and B B′ a syncline, and the arrows show the dip on either side of the axes and also the general dip of the whole northward. Fig. 156 is a section of the same. The sinuosity of the outcrop is, of course, the necessary result of the folding and tilting. We have supposed the strata folded and tilted, and then

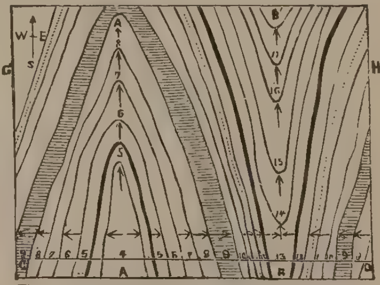

Fig. 158.—Plan of Undulating Strata. The arrows show the direction of dip.

showed what the outcrop would be. The field geologist, of course, follows the reverse method: he works out the outcrop, and infers the structure and position of strata. If the strata had been simply folded but not tilted, then the outcrop of the same section (Fig 156) would be much simpler, i. e., in parallel lines as in Fig. 159.

The cases represented by these figures are comparatively simple, and we have supposed the soil removed, so that the outcrop is easily traced. But when we remember—1. The great complexity of the outcrop often produced by folding and tilting; 2. That it is very much increased by inequalities of erosion; 3. That it is still further increased by fissuring and displacement; and, worst of all, 4. That the rocks are largely covered by soil—we easily see the difficulty of the task of making a good geological map and section of any region.

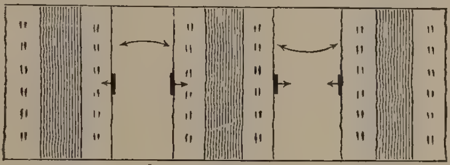

Fig. 159.—The arrows show the direction of dip.

Conformity and Unconformity.—We have just seen that all land-surfaces are deeply eroded and the strata are left with their edges exposed. We have also seen (pp. 140–145) that the crust of the earth is everywhere in a state of slow movement: in some places sea-bottoms are rising and becoming land-surfaces, in others land-surfaces are sinking to become sea-bottoms. Now, the same thing has taken place in earlier geological times. Suppose, then, an eroded land-surface with the strata-edges exposed, to sink down and become ocean-bottom, and receive sediments covering the strata-edges and filling the erosion-hollows, and afterward to rise again and be submitted to the inspection of the geologist; Fig. 160 represents in section what he would see. They are interpreted as follows: In A and B the lower

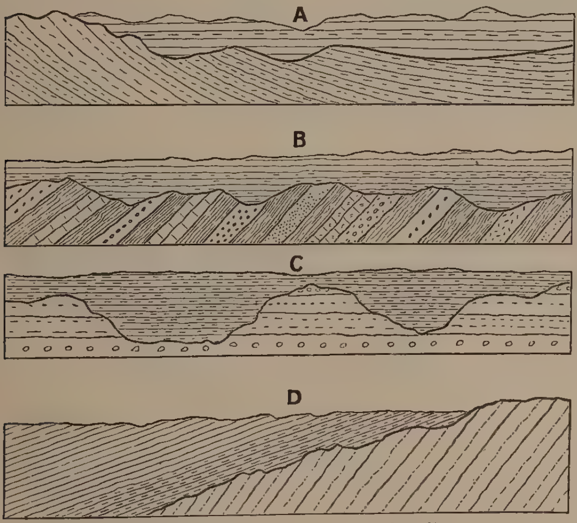

Fig. 160.—Some Cases of Unconformity.

series of strata was first deposited; then the sea-bottom was raised to land-surface and the strata tilted and eroded; then it went down again and received the upper series; and, finally, was raised and inspected by the geologist. In C the process was the same, except that the first series of strata was raised *without tilting*. In D the second series of strata *was also tilted* in the second raising. Now, the strata of each series are said to be conformable among themselves, but the two series are unconformable with one another.

Definition.—Therefore, strata are said to be conformable when they are *parallel*, *continuous*, and therefore *formed under the same conditions*, and are unconformable when they are *discontinuous*, and formed under different conditions; the discontinuity being *always marked by an old eroded land-surface.* Unconformable strata are usually non-parallel, and this is often made a part of the definition; but this is not necessary. In Fig. 160, C, there is no want of parallelism. The reason we have already explained.

A section like any one of the foregoing—among the commonest in geology—reveals many interesting events: 1. A long period of quiet, during which sediments of the first series were deposited continuously on a sea-bottom. The length of this period is measured by the thickness of the series. 2. A period of elevation, during which the sea-bottom became land-surface. We have no means of estimating the length of this period. 3. A long period during which the land-surface became deeply eroded. The length of this period is measured by the amount of erosion. 4. A period of subsidence, during which the land-surface became sea-bottom. We can not estimate the length of this. 5. A long period of quiet, during which the second series of sediments was continuously deposited. This period is estimated by the thickness of the sediments. 6. Another period of elevation by which the whole was brought into view. Therefore a line of unconformity marks a land-surface period between two sea-bottom periods at that place. It is evident that the first stratum above a line of unconformity is usually a *conglomerate*, marking an old sea-beach. The process is more fully explained in connection with a concrete example on page 306 of Part III.

It is evident, then, that every case of unconformity represents a gap in the geological record *at that place;* for the geological record is written on strata, and unconformity means a land-surface period, during which there was erosion instead of sedimentation, record-destroying instead of record-making. The gap may be filled and the record recovered by sediments formed at that time in some other place. This is usually the case, but not always. The loss of record may be partly by erosion, but mostly because not written at that place.

Now, such unconformities and lost records are, as we have seen, the result of crust oscillations. But crust oscillations produce necessarily changes in physical geography, and therefore changes of climate, and therefore also changes of faunas and floras. They consequently mark the great divisions and subdivisions of geological history.

Geological Formations.—A group of strata conformable throughout and containing continuous record, and separated from other conformable groups by a line of unconformity, is called a *geological formation*. There are, however, other tests of a formation, by which hereafter we will complete the definition.

Cleavage Structure.[*]

We have thus far spoken only of the original and universal structure of stratified rocks, together with the tiltings, foldings, and erosion, to which they have been subjected. There is, however, often found in stratified rocks a *superinduced* structure which simulates, and is often mistaken for stratification. It is called *cleavage structure*, or (since it is usually found in slates) *slaty cleavage*. This subject has recently attracted much attention, and is an admirable example of the successful application of physics to the solution of problems in geology.

Cleavage may be defined as the easy splitting of any substance in planes parallel to each other. Such definite splitting may result, in different cases, from entirely different causes. For example (*a*), under the influence of the sorting power of water, sedimentary materials may be so arranged as to give rise to easy splitting along the planes of lamination. Many rocks may be thus split into large coarse slabs called flag-stones, and are used for paving streets, or even sometimes as roofing-slates. This may be called *flag-stone cleavage*, or lamination cleavage. Again (*b*), the arrangement of the ultimate molecules of a mineral under the influence of molecular or crystalline forces gives rise to an exquisite splitting along the planes parallel to the fundamental faces of the crystal. This is called *crystalline cleavage*. Again (*c*), the arrangement of the wood-cells under the influence of vital forces gives rise to easy splitting of wood in the direction of the silver-grain. This may be called *organic cleavage*.

Now, in certain slates and some other rocks is found a very perfect cleavage on a stupendous scale. Whole mountains of strata may be cleft from top to bottom in thin slabs, along planes parallel to each other. The planes of cleavage seem to have no relation to the strata, but cut through them, maintaining their parallelism, however the strata may vary in dip (Fig. 161). Usually the cleavage-planes are highly inclined, and often nearly perpendicular. It is from the cleaving of such slates that roofing-slates, ciphering-slates, and blackboard-slates are made. This remarkable structure has long excited the interest of geologists, and many theories have been proposed to explain it.

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[*] This structure is usually treated under metamorphic rocks, as a kind of metamorphism; but it is found in rocks which have not undergone ordinary metamorphic changes, and it is produced by an entirely different cause.

On cursory examination of such rocks, the first impression is, that the cleavage is but a very perfect example of flag-stone or lamination cleavage — that the cleavage-planes are in fact stratification-planes, and that we have here an admirable example of finely laminated rocks which have been highly tilted and then the edges exposed by erosion. Closer examination, however, will generally show the falseness of this view. Fig. 162 represents a mass of slate in which three kinds of structure are distinctly seen, viz., *joint faces*, *A*, *B*, *C*, *J*, *J*; *stratification-planes*, *S S S*, gently dipping to the right; and *cleavage-planes*, highly inclined, *D D*, cutting through both. Cleavage-planes are therefore not stratification-planes.

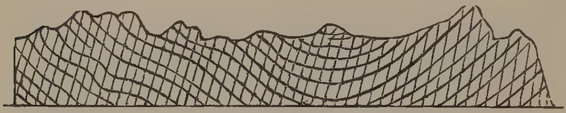

FIG. 161.—Cleavage-Planes cutting through Strata.

Again, it has been compared to crystalline cleavage, on a huge scale. It has been supposed that electricity traversing the earth in certain directions, while certain rocks were in a semi-fluid or plastic state through heat, arranged the particles of such rocks in a definite way, giving rise to easy splitting in definite directions. In support of this view it was urged that cleaved slates are most common in metamorphic regions; and metamorphism, as we shall see hereafter (p. 221 *et seq.*), indicates the previous plastic state of rocks, which is a necessary condition of the rearrangement of the particles by electricity. The great objections to this theory are—1. That the cleavage is not like crystalline cleavage, between ultimate molecules, and therefore perfectly smooth, but between discreet and quite visible granules; and, 2. That although the phenomenon is indeed most common in metamorphic rocks, yet metamorphism is by no means a necessary condition; on the contrary, when the real necessary conditions are present, the less the metamorphism the more perfect the cleavage.

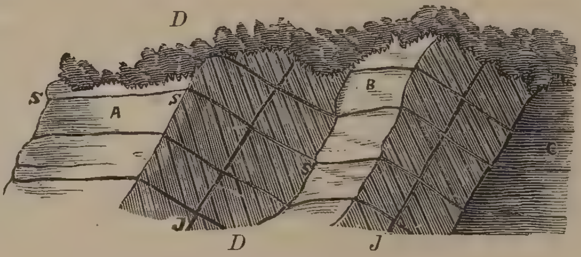

FIG. 162.—Strata, Cleavage-Planes, and Joints.

It is evident, therefore, that slaty cleavage is not due to any of the causes spoken of above. It is not flag-stone cleavage, nor crystalline cleavage, and of course can not be organic cleavage.

Sharpe's Mechanical Theory.—The first decided step in the right direction was made by Sharpe. According to him, *slaty cleavage is always due to powerful pressure at right angles to the planes of cleavage, by which the pressed mass has been compressed in the direction of pressure and extended in the direction of the dip of the cleavage planes.* This theory may be now regarded as completely established by the labors of Sharpe, Sorby, Haughton, Tyndall, and others. We will give a few of the most important observations which establish its truth.

(*a*) *Distorted Shells.*—Many cleaved slates are full of fossils. In such cases the fossils are always crushed and distorted as if by powerful pressure, their diameter being shortened at right angles to the cleavage, and greatly increased in the direction of the cleavage-planes. The following figures (Fig. 163) are examples of distortion by pressure. In Fig. 163, *Z Z* gives the direction of the planes of cleavage; Figs. 1, 2, 3, 4, represent one species; 5, 6, 7, 8, another. In Fig. 164 still another species is represented in the natural and distorted forms.

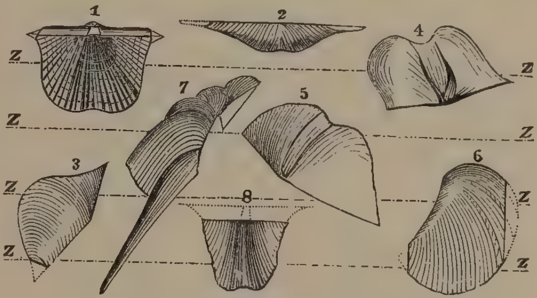

Fig. 163.—Distorted Fossils (after Sharpe).

(*b*) *Association with Foldings.*—Cleavage is always associated with *strong* foldings and contortions of the *strata.* The folding of the strata is produced by *horizontal* pressure; the strike of the strata, or the direction of the anticlinal and synclinal axes, being of course atright angles to the direction of pressure. Now, if cleavage is produced by the same pressure which folded the strata, then in this case we ought to find the cleavage-planes highly inclined, and there strike parallel with the strike of the strata; and such we find is usually the fact. In Fig. 165 the heavy lines represent the strata and the light lines the cleavage-planes, both outcropping on a nearly level surface, and parallel to each other.

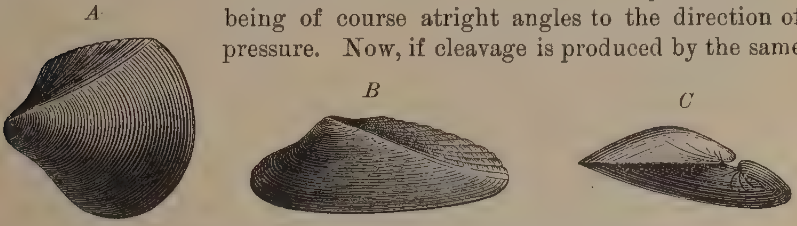

Fig. 164.—Cardium Hillanum : *A*, natural form; *B* and *C*, deformed by pressure.

(*c*) *Association with Contorted Laminæ.*—The last evidence was taken from foldings on a grand scale of the crust of the earth; but even fine lines of lamination are often thrown into intricate foldings by squeezing together in the direction of the lamination-planes. In such case, of course, the cleavage ought by theory to be at right angles to the original direction of the lamination, and in such direction we actually find them. Fig. 166 represents a block of rock in which three lamination-lines are visible. The lower one, *f d*, consists of coarse sand which could not mash, and therefore has been thrown into folds. As the specimen stands in the figure, the pressure has been horizontal; the perpendicular lines represent the position of the cleavage-planes. Fig. 167 represents a beautiful specimen of laminated slate, in which the lamination-planes have been thrown into folds by pressure. The direction of the pressure is obvious. The planes of cleavage are parallel to the face, *c p*, and therefore at right angles to the pressure.

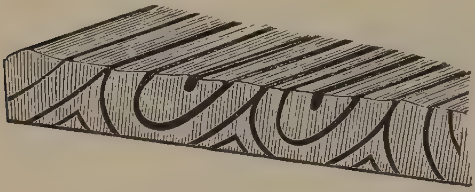
Fig. 165.—Cleavage-Planes intersecting Strata.

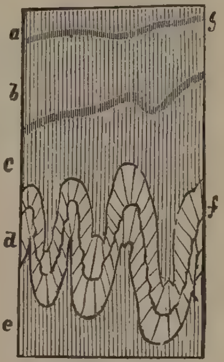

Fig. 166.—Cleavage-Planes (after Tyndall).

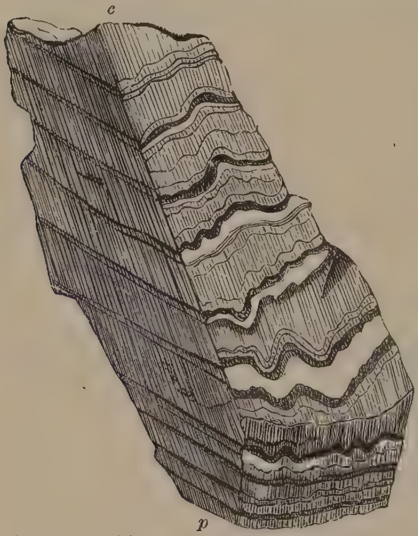

Fig. 167.—A Block of Cleaved Slate (after Jukes).

(*d*) *Flattened Nodules.*—In some finely-cleaved slates, such as are used for writing-slates, it is common to find small light-greenish, elliptical spots of finer material. In clay-deposits of the present day it is also common to find imbedded little round nodules of finer material. It is probable that the greenish nodules in slate were also rounded nodules of finer clay in the original clay-deposit from which the slate was formed by consolidation. But in cleaved slates these nodules are always very much flattened in the direction at right angles to the cleavage-planes, and spread out in the direction of these planes.

(*e*) *Experimental Proof.*—Finally, experiments by Sorby and by Tyndall show that clay (the basis of slates), when subjected to powerful pressure, exhibits always a cleavage, often a very perfect cleavage, at right angles to the line of pressure.

Physical Theory.—Cleavage is certainly produced by pressure, but the question still remains: How does pressure produce planes of easy splitting at right angles to its own direction? What is the physical explanation of cleavage?

Sorby's Theory.*—Mr. Sorby's view is that all cleaved rocks consisted, at the time when this structure was impressed upon it, of a plastic mass, with *unequiaxed incompressible foreign particles* disseminated through it; and that *by pressure the unexquiaxed particles were turned so as to bring their long diameters in a direction more or less nearly at right angles to the line of pressure, and thus determined planes of easy fracture in that direction.* Usually, as in slates, the plastic material is clay, and the unequiaxed particles are mica-scales. Let *A*, Fig. 168, represent a cube of clay with mica disseminated. If such a cube be dried and broken, the fracture will take place principally along the surfaces of the mica, which may therefore be seen glistening on the uneven surface of the fracture; but if the cube, while still plastic, be pressed into a flattened disk, then the scales are turned with their long diameters in the direction of extension and at right angles to the line of pressure, as in *B*, Fig. 168, and the planes of easy fracture, being still determined by these surfaces, will be in that direction.

In proof of this view, Mr. Sorby mixed clay with mica-scales or with oxide-of-iron scales, and, upon subjecting the mass to powerful compression and drying, he always found a perfect cleavage at right angles to the line of pressure. Furthermore, by microscopic examination he found that both in the pressed clay and in the cleaved slates the mica-scales lay in the direction of the cleavage-planes.

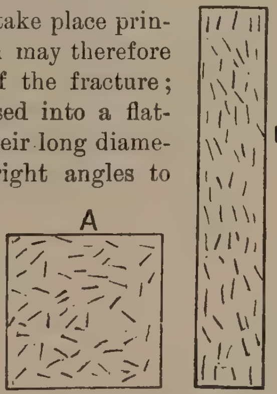

Fig. 168.—Illustrating Sorby's Theory of Slaty Cleavage (after Sorby).

Although cleavage is most perfect in slates, yet other rocks are sometimes affected with this structure. In a specimen of cleaved limestone, Sorby found under the microscope unequiaxed fragments of broken shells, corals, crinoid stems, etc. (organic particles), in a homogeneous limestone-paste, lying with their long diameters in the direction of cleavage. Originally the limestone was a lime-mud with (he supposes) unequiaxed organic particles disseminated. In some cases, however, Sorby recognized the very important fact that the organic fragments which were encrinal joints, had been *flattened by pressure*—had *changed their form* instead of their position. *A*, Fig. 169, gives a section of the mass in the supposed original condition, and *B* the condition after pressure. This observation contained the germ of the theory proposed by Tyndall.

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* Philosophical Magazine, second series, vol. xi, p. 20.

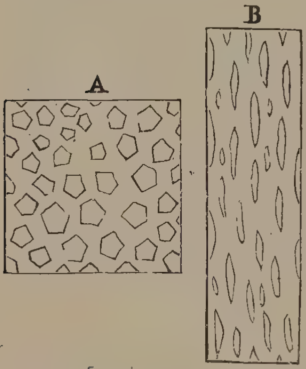

Fig. 169.—Illustrating Sorby's Theory of Slaty Cleavage (after Sorby).

Tyndall's Theory.[*]—Tyndall was led to reject Sorby's theory by the observation that cleavage structure was not confined to masses containing unequiaxed particles of any kind, but, on the contrary, the cleavage is more perfect in proportion as the mass is free from all such particles. Clay, deprived of the last trace of foreign particles by the sorting power of water, when pressed, cleaved in the most perfect manner. Common beeswax, flattened by powerful pressure between two plates of glass and then hardened by cold, exhibits a most beautiful cleavage structure. Almost any substance—curds, white-lead powder, plumbago—subjected to powerful pressure, exhibits to some extent a similar structure. Tyndall explains these facts thus: Nearly all substances, except vitreous, have a granular or a crystalline structure, i. e., consist *entirely* of discrete granules or crystals, with surfaces of easy fracture between them. When such substances are broken, the fracture takes place between the crystals or granules, producing a rough crystalline or granular surface, entirely different from the smooth surface of vitreous fracture. Marble, cast iron, earthenware, and clay, are good examples of crystalline and granular structure. Now, if a mass thus composed yield to pressure, every constituent granule is flattened into a scale, and the structure becomes *scaly;* and as the surfaces of easy fracture will still be between the constituent scales, we have cleavage at right angles to the line of pressure. A mass of iron, just taken from the puddling-furnace and cooled, exhibits a *granular* structure; but if drawn out into a bar, each granule is extended into a thread, and the structure becomes *fibrous;* or if rolled into a sheet, each granule is flattened into a scale, and we have a *cleavage structure.*

There can be little doubt that this is the true explanation of slaty cleavage. The change of form which, as we have seen, has taken place in the fossil-shells, encrinal joints, and rounded nodules, has affected every constituent granule of the original earthy mass, so that the structure becomes essentially scaly instead of granular; the cleavage being between the constituent scales. Sorby, it is true, in his observations on cleavage limestones, recognized the true cause of cleavage, viz., the *change of form* of discrete particles; but he regarded this as subordinate to change of position. Besides, the particles of Sorby were *foreign*, which Tyndall has shown to be unnecessary; while the particles of Tyndall are *constituent.*

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[*] Philosophical Magazine, second series, vol. xii, p. 35.

Geological Application.—It may be considered, therefore, as certain that cleaved slates have assumed their peculiar structure under the influence of powerful pressure at right angles to the cleavage-planes, by which the whole squeezed mass is mashed together in one direction and extended in another. Taking any ideal sphere in the original unsqueezed mass: after mashing the diameter in the line of pressure has been shortened, the diameter in the line of cleavage-*dip* has been correspondingly extended, and the diameter in the line of cleavage-strike unaffected (since extension of this diameter in any place must be compensated by shortening in a contiguous place right or left); so that the original sphere has been converted into a greatly-flattened ellipsoid of three unequal diameters. The *amount* of compression and extension may be estimated in the case *a* by the amount of distortion of shells of known form (Figs. 163 and 164); in the case *c* by a comparison of the transverse diameter of the block with the length of the folded line *f d* (Fig. 166); in the case *d* by the relation between the diameters of the elliptic spots. By these means, but principally by the first, Haughton * has estimated that an original ideal sphere has been changed into an ellipsoid, whose greatest and shortest diameters are to each other, in some cases, as 2 : 1, in others as 3 : 1, 4 : 1, 6 or 7 : 1, 9 : 1, and in some even 11 : 1. The average in well-cleaved slates, according to Sorby, is about 6 : 1. Now, since this ratio is the result partly of compression and partly of extension, it is evident that either the compression alone or the extension alone would be the square roots of these ratios. Therefore, we may assume the average compression as 2½ : 1, and the average extension as 1 : 2½.

It is impossible to overestimate the geological importance of these facts. Whole mountains of strata, whole regions of the earth's crust, are cleaved to great and unknown depths, showing that the crust has been subjected to an almost inconceivable force, squeezing it together in an horizontal direction and swelling it upward. This upward swelling, or thickening of the strata by lateral squeezing, is a probable cause of gradual elevation of the earth's crust, which has not been sufficiently noticed by geologists. We will speak again of this important subject in our discussion of mountain-formation.

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* Philosophical Magazine, fourth series, vol. xii, p. 409.

There are reasons for believing that the squeezing did not take place, and the structure was not formed, while the strata were in their original condition of plastic sediment, but after they had been consolidated into rock and the contained fossils had been completely petrified, otherwise the shells must have been broken by the pressure. Yet, on the other hand, some degree of plasticity seems absolutely necessary to account for so great a compression in one direction and extension in another without disintegration of the mass. It seems most probable that at the time the structure was produced these rocks were deeply buried beneath other rocks and in a somewhat plastic state, through the influence of heat in the presence of water. Afterward, they were exposed by erosion.

Nodular or Concretionary Structure.

In many stratified rocks are found nodules of various forms scattered through the mass or in layers parallel to the planes of stratification. Like slaty cleavage, this structure is the result of internal changes subsequent to the sedimentation; for the planes of stratification often pass directly through the nodules (Figs. 170 and 171). The flint nodules of the chalk, and the clay iron-stone nodules of the coal strata and hydraulic lime-balls, common in many clays, are familiar illustrations of this structure.

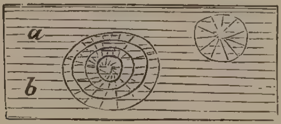

FIG. 170.

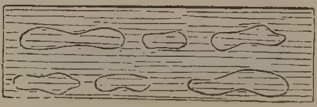

FIG. 171.

Cause.—Nodular concretions seem to occur whenever a more soluble or more suspensible substance is diffused in small quantities through a mass of entirely different and more fixed material. Thus, if strata of sandstone or clay have small quantities of carbonate of lime or carbonate of iron diffused through them, the diffused particles of lime or iron will gradually, by a process little understood, segregate themselves into more or less spherical or nodular masses, in some cases almost pure, but generally inclosing a considerable quantity of the material of the strata. In this manner lime-balls and iron-ore balls and nodules, so common in sandstones and clays, are formed. In like manner, the flint nodules of the chalk were formed by the segregation of silica, originally diffused in small quantities through the chalk-sediment. Very often some foreign substance forms the nucleus about which the segregation commences. On breaking a nodule open, a shell or some other organism is often found beautifully preserved. These nodules, therefore, are a fruitful source of beautiful fossils. In most cases, probably in all cases, the segregating substance must have been to some extent soluble in water pervading, or suspensible in water percolating the stratum; *and the reason* why they are so frequently associated with fossils is that decomposing organic matter renders many substances such as lime carbonate, iron oxide, and silica more *soluble.* Sometimes the nodules run together, forming a more or less continuous stratum (Fig. 176). In such cases, the segregating material is more impure.

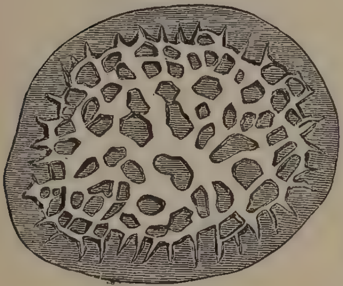

FIG. 172.

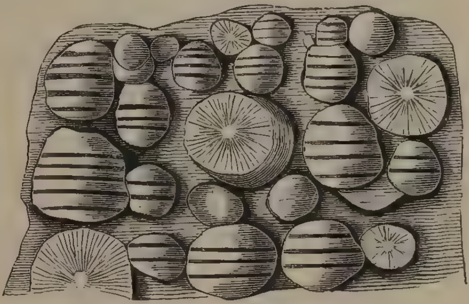

FIG. 173.—Dolomite containing Concretions, Sunderland (after Jukes).

Forms of Nodules.—The typical and most common form is *globular.* This is well seen in lime-balls and iron-balls. Sometimes these balls are solid, sometimes they have irregular cracks in the center (Fig. 172), sometimes they have a radiated structure (Fig. 173), sometimes they are hollow like a shell (this is common in iron balls). They vary in size from that of a pea to six and eight feet in diameter.

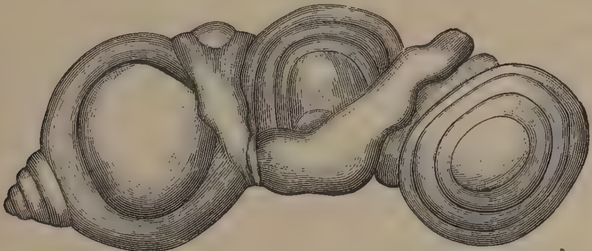

FIG. 174.—A Curious Form of Concretion (after Gratacap).

Often, however, instead of the spherical form, they take on various and strange and fantastic shapes (Fig. 174), sometimes like a dumb-bell, sometimes a flattened disk, sometimes a ring, sometimes a flattened ellipsoid, regularly seamed on the surface like the shell of a turtle

(turtle-stones). They are often mistaken by unscientific observers for fossils.

Kinds of Nodules found in Different Strata.—In sandstone strata the nodules are commonly carbonate of lime or oxide of iron (lime or iron-balls). In *clay strata* they are carbonate of lime or carbonate of iron (clay iron-stone of coal strata), or a mixture of these (Roman cement nodules of the London clay).

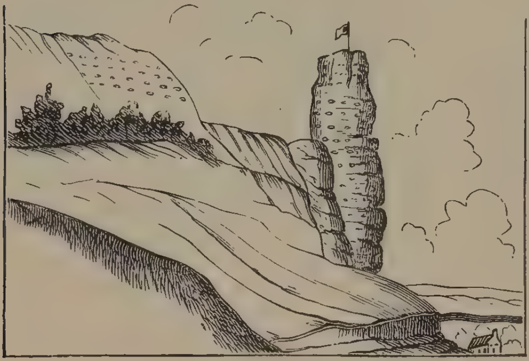
Fig. 175.—Chalk-Cliffs with Flint Nodules.

In pure limestone the nodules are always silica, and conversely pure silica nodules are peculiar to limestone. The flint nodules of the chalk are remarkable for being arranged in planes parallel to the planes of stratification (Fig. 175). Sometimes the siliceous matter segregates in continuous strata of siliceous limestone (Fig. 176).

In the cases thus far spoken of, the nodules are scattered through the mass of the strata or arranged in planes parallel to the planes of stratification. But in some cases the whole mass of the rock assumes a concretionary or concentric structure. The cause of this is still more difficult to explain.

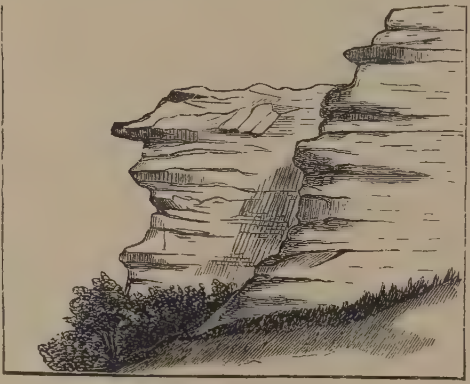
Fig. 176.—Chalk-Cliffs.

Fossils: their Origin and Distribution.

Stratified rocks, as we have already seen, are sediments accumulated in ancient seas, lakes, deltas, etc., and consolidated by time. As now, so *then*, dead shells were imbedded in shore-deposits; leaves and logs of high land-plants, and bones of land-animals, were drifted into swamps and deltas and buried in mud; and tracks were formed on flat, muddy shores by animals walking on them. These have been preserved with more or less change, and are even now found in great numbers inclosed in stratified rocks. They are called *fossils.* A fossil, therefore, is any evidence of the former existence of a living being. Fossils are the remains of the faunas and floras of previous geological epochs. Th~~ere~~ presence is the most constant characteristic of stratified rocks.

Degrees of Preservation.—Sometimes only the tracks of animals, or impressions of leaves of plants, are preserved. More commonly the bones or shells, or other hard parts of animals, are preserved with various degrees of change. Sometimes even the soft and more perishable tissues are preserved. We will treat of these degrees under three principal heads.

1. *Decomposition prevented and the Organic Matter more or less completely preserved.*—Cases of this kind are usually found in comparatively *recent* strata, and imbedded either in *frozen soils*, or in *peat*, or in *stiff clays ;* although some cases of partial preservation of the organic matter are found even in old rocks. Extinct elephants have been found frozen in the river-bluffs of Siberia so perfectly preserved that dogs and wolves ate their flesh. Skeletons of men and animals are found in peat-bogs and stiff clays of a comparatively recent formation, the organic matter of which is still preserved. In clays of the Tertiary period the imbedded shells still retain the epidermis, and even in the Lias (Mesozoic) shells are found retaining the nacreous luster. Coal is vegetable matter changed but not destroyed. It is found in almost every formation, even down to the oldest. Every degree of change may be traced in different specimens of fossil wood, between perfect wood and perfect coal.

2. *Petrifaction: Organic Form and Structure preserved.*—In the last case the *organic matter* is more or less preserved. In the case now to be described the organic matter is entirely gone; but the *organic form* and the *organic structure* are preserved in mineral matter. This is what is usually called petrifaction or mineralization. The best example of this is *petrified wood.* In a good specimen of petrified wood, not only the external form of the trunk, not only the general structure of the stem—viz., pith, wood, and bark—not only the radiating silver-grain and the concentric rings of growth, are discernible, but even the microscopic cellular structure of the wood, and the exquisite sculpturings of the cell-walls themselves, are perfectly preserved, so that the kind of wood may often be determined by the microscope with the utmost certainty. Yet not one particle of the organic matter of the wood remains. It has been entirely replaced by mineral matter; usually by some form of silica. The same is true of shells and bones of animals; but as shells and bones consist naturally partly of organic and partly of mineral matter, very often it is only the organic matter

which is replaced, although sometimes the original mineral matter is also replaced by silica or other mineral substance. The radiating structure of corals or the microscopic structure of teeth, bones, and shells, is often beautifully preserved. This kind of preservation for shells and corals is most common in limestones and clays; for wood, in gravels.

Theory of Petrifaction.—If wood be soaked in a strong solution of sulphate of iron (copperas) and dried, and the same process be repeated until the wood is highly charged with this salt, and then burned, the structure of the wood will be roughly preserved in the peroxide of iron left. Also, it is well known that the smallest fissures and cavities in rocks are speedily filled by infiltrating waters with mineral matters. Now, wood buried in soil soaked with some petrifying material becomes highly charged with the same, and the cells filled with infiltrated matter, and when the wood decays the petrifying material is left, retaining the structure of the wood. But this is not all, for in Nature there is an *additional process*, not illustrated either by the experiment or by the example of infiltrated fillings. As each particle of organic matter passes away by decay, a particle of mineral matter takes its place, until finally the whole of the organic matter is replaced. Petrifaction, therefore, is a process of *substitution*, as well as interstitial filling. Now, it so happens, probably from the different nature of the process in the two cases, that the interstitial filling always differs, either in chemical composition or in color, from the substituted material. Thus the structure is still visible, though the mass is solid. If Fig. 177 represent a cross-section of three petrified wood-cells, the matter filling the cells (*b*) is always different from the matter forming the cell-wall (*a*).

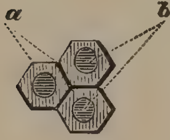

Fig. 177.

The most common petrifying materials are silica, carbonate of lime, and sulphide of iron (pyrites). In the case of petrifaction by pyrites the process is quite intelligible, but the structure is usually very imperfectly preserved. If water containing sulphate of iron ($FeSO_4$) come in contact with decaying organic matter, the salt is deoxidized by the organic matter, the latter passing off as carbonic acid and water, and the former becomes insoluble sulphide (FeS_2), and is deposited. Now, as each particle of organic matter passes away as CO_2 and H^2O, the molecule of iron sulphate which effected the change is itself changed into insoluble sulphide, and takes its place.

The process of replacement by silica (silicification) is less clear, but it is probably as follows: Silica is found in solution in many waters, being held in this condition by small quantities of alkali present in the waters. In contact with decomposing wood the *alkali is neutralized by the humic, ulmic, and other acids of decomposition, and the silica therefore deposited.*

3. *Organic Form only preserved.*—In the third case organic matter and organic structure are both lost, and only organic form is preserved. This kind of fossilization is most commonly seen in shells. It may be subdivided into four subordinate cases, represented in section by *a*, *b*, *c*, and *d* of Fig. 178. In this figure the horizontal lines represent the original sediment which may or may not have consolidated into rock; the vertical lines represent a subsequent filling of different and usually finer material. In *a* we have a *mold of the external form* of the shell preserved in sediment. The shell with the undecayed animal was imbedded, and afterward entirely dissolved away, leaving only the hollow mold. In *b* the same process has taken place, only the mold has been subsequently filled by infiltration of slightly soluble matters. In this case we have both the *mold* and the cast of the *external form;* the mold being formed of sediment, and the cast of infiltrated matter. These are always of different materials, i. e., different either in chemical composition or in state of aggregation. In *c* we have a *mold of the external* form in sediment, and a cast of the *internal* form in the *same* material with an empty space between, having the exact form and thickness of the shell. In this case, the already dead and empty shell was imbedded in sediment, *which also filled its interior;* afterward the shell was removed, leaving an empty space. In *d* this empty space was subsequently filled by infiltration. In shore and river deposits of the present day it is very common to find shells imbedded in, and filled with, sand or mud. In the more recent tertiary rocks shells are commonly found in the same condition precisely; but in the older rocks more commonly the original shell is removed, and the space either left empty or filled by infiltration. Cases *c* and *d* are well represented

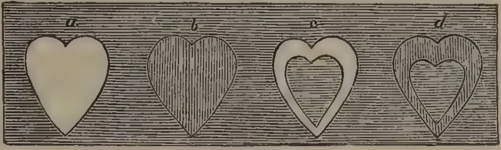

FIG. 178.

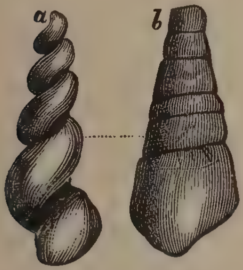

FIG. 179.—*a*, Cast of interior; *b*, natural form.

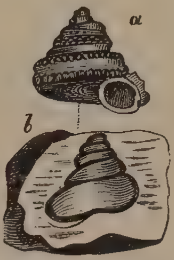

FIG. 180.—*a*, Natural form; *b*, cast of interior and mold of exterior.

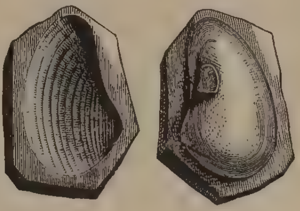
FIG. 181.—Trigonia Longa, showing cast (*a*) of the exterior and (*b*) of the interior of the shell.

by Figs. 179, 180, and 181. Cases like *a* and *c* are most commonly found in porous rocks like sandstone; *b* and *d*, especially the latter, are found in all kinds of rocks. By far the most common *infiltration* fillings are *carbonate of lime* and *silica.*

Often we find impressions of the forms of *small portions only* of the original organism, as of the leaves of trees, or the feet of animals walking on the soft mud of the flat shores of ancient bays. Such tracks were afterward covered up with river or tidal deposit, and thus preserved. On cleaving the rock along the lamination-planes we have on one side a mold and on the other the cast of the *foot.*

Between cases 1 and 2 every stage of gradation may be traced. The amount of change, as a general fact, varies with the age of the rock; but is still more dependent on the kind of rock and the degree of metamorphism. In an impermeable rock, like clay, the changes are much more slow than in a porous rock, like sandstone.

Distribution of Fossils in the Strata.

The nature of the fossil species found in rocks is determined partly by the *kind* of rock, partly by the *country* where the rock is found, and partly by the *age* of the rock.

1. **Kind of Rock.**—It is well known that the species of lower marine animals vary with the depth. They also vary with the kind of bottom. Thus, along shore-lines and on sand-bottom the species differ from those in deep water and on mud-bottom. Shells are found mostly along shore-lines, corals in opener seas, and foraminifera in deep seas. The same was true in every previous epoch. We might expect, therefore, and do find, that the lower marine fossils of sandstones, shales, and limestones, differ even when these strata belong to the same country and geological epoch. The higher marine animals, such as fishes, cuttle-fish, etc., swimming freely in the sea, are more independent of bottoms, and we find their skeletons and shells equally in all kinds of strata. Land animals perish on land, and their skeletons are drifted into bays, river-deltas, and lakes, and buried there mostly in fresh-water or brackish-water deposits of sand and clay. It is, therefore, in such strata that their remains are commonly found.

2. **The Country where found.**—It is also well known that the faunas and floras of different countries at the present time differ as to species, and often as to genera and families; the difference being generally in proportion to the difference in climate, the physical barriers intervening, and the length of time during which the barriers have existed. The same was true of the faunas and floras of previous epochs, and therefore of the fossils of the same age in different countries. The fossil species of the same epoch in America, in Europe, and in Asia are not usually identical, although there may be a general

resemblance. The geographical diversity, however, is small in the lowest and oldest rocks, and becomes on the whole greater and greater as we pass upward into newer and newer rocks, and is greatest in the fauna and flora of the present day.

3. **The Age.**—This introduces the subject of the laws of distribution of organisms in *time*, or of fossils vertically in the series of stratified rocks. The subject will be more fully treated in Part III, of which it constitutes the principal portion. We now bring out only so much as is necessary as a basis of classification of stratified rocks.

(*a*) *Geological Fauna and Flora and Corresponding Geological Period and Geological Formation.*—As we pass from the oldest and lowest rocks upward to the newest and highest, we find that *all* the species, most of the genera, and many of the families, change many times. Now, all the species of animals and plants inhabiting the earth at one time constitute the fauna and flora of that geological time. Geological faunas, therefore, have changed many times. *In a conformable* series of rocks the change from one fossil fauna or flora to another succeeding is always *gradual*, the species of the later fauna or flora gradually replacing those of the earlier. But between two series of *unconformable* strata the change is sudden and complete—as if one fauna and flora had been suddenly destroyed and another introduced. It must be remembered, however, that unconformity always indicates a great lapse of time unrepresented at the place of observation by strata or fossils. It is therefore probable that the apparent suddenness of the change is only the result of our ignorance of the fauna and flora of the period unrepresented, and this is confirmed whenever we find the intermediate strata. Nevertheless, as unconformity always indicates changes of physical geography, and therefore of climate, it is probable that in the history of the earth there were periods of great changes, marked by unconformity of strata, during which *changes of species were more rapid*, separated by *periods of comparative quiet, marked by conformity*, during which the species were either *unchanged*, or *changed slowly.* Such a period is called a geological period or geological epoch, and the rocks formed during a geological period, or epoch, is called a *formation.*

There are, therefore, two tests of a formation and a corresponding geological period, viz., 1. Conformity of the strata or *rock-system*, and, 2. General similarity of fossils, or *life-system.* There are also two modes of separating formations and corresponding periods, viz., unconformity of the rock-system, and great and sudden change of the life-system. A geological formation, therefore, may be defined as a group of conformable rocks containing *similar fossils*, usually separated from other similar groups containing different fossils by unconformity. A geological period may be defined as a period of comparative quiet, during which the physical geography, climate, and fauna and flora were substantially the same, usually separated from other similar periods by changes of physical geography and climate, which resulted in changes of fauna and flora. Of these two tests, however, the life-system is usually considered the most important, and in case of disagreement must control classification.

(*b*) *Geological Faunas and Floras differ more than Geographical Faunas and Floras.*—If there were no geographical diversity, species of the same age would be identical all over the earth, and therefore it would be easy to determine strata of the same age (geological horizon). On the other hand, if geographical diversity in any age were as great as the diversity between two successive ages, then it would seem impossible to establish a geological horizon. But this law states that the difference between two *successive* faunas is greater than between two *contiguous* faunas. In other words, the species of successive periods, or fossils of successive formations, differ from each other more than species of the same period or fossils of the same formation in different parts of the earth. There is a general similarity in the species of the same period all over the surface of the earth. Hence by comparison of fossils it is possible to determine what strata, in different portions of the earth, belong to the same period (to synchronize strata). The strata *all over the earth*, which were formed at the same time, are said to belong to the same *geological horizon*. Strata of the same horizon are determinable by similarity of fossils with considerable certainty, until we come up to the tertiary rocks. In all the newer rocks, however, the geographical diversity is so great as to interfere seriously with the ability to synchronize by means of comparison of fossils. Another method, therefore, is used for these higher rocks.

(*c*) *Increasing Likeness to Existing Forms.*—By examining and comparing fossils from the lowest to the highest rocks, it has been observed that there is a steady approach of the fossil faunas and floras to the present faunas and floras, first in the families, then in the genera, and finally in the species. The species of fossil molluscous shells begin to be identical with molluscous species of the present day only in the *tertiary* rocks, and the proportion of identical species steadily increases as we pass upward. Thus in the newer rocks, just where the other method (comparison of fossil faunas with one another) begins to fail, we may synchronize strata of different localities, by comparing their shell fauna with the shell fauna of the present day, in the same localities. *Those are said to be of the same age which contain the same percentage of shells identical with those of the present day.* To this we may add that, if not *species*, at least many genera and families, especially among vertebrates, are characteristic of each horizon even of the newest rocks.

SECTION 2.—CLASSIFICATION OF STRATIFIED ROCKS.

Geology is essentially a history. Stratified rocks are the leaves on which this history is recorded. The fundamental idea of every classification is therefore *relative age.* The object to be attained in classification is, *first*, to arrange all rocks in chronological order, so that the history may be read as it was written; and then, *second*, to collect them into larger and smaller groups, called *systems*, *series*, *formations*, corresponding to the great *eras*, *periods*, *epochs*, of the earth's history. There are several different methods of determining the relative age of rocks:

1. **Order of Superposition.**—It is evident, from the manner in which stratified rocks are formed—viz., by *sedimentation*—that their original position indicates, with absolute certainty, their relative age, the lower being older than the higher. If, therefore, the original position of any series of strata be retained or not very greatly disturbed, and we have a good section, the relative age of the strata which compose the series may be easily determined. But the strata, as we have already seen, have in many cases been crushed and contorted and folded in the most intricate manner, sometimes even turned over; they have also been broken and slipped, and large masses carried away by erosion, and often so changed by heat and other agents, that their stratification is nearly or quite obliterated. For these reasons it is often very difficult to determine the relative position, and thus to construct an ideal section of the strata of a series of rocks, even in a single locality. Nevertheless, the method of superposition is conclusive, and takes precedence of all others whenever it can be applied. In spite of all these difficulties, if the whole geological series were present in any one locality, it would be comparatively easy to construct the geological chronology.

But a series of rocks *in any one locality* can not give us the whole history of the earth. Since sedimentation only takes place at the bottom of water, those places which were *land-surfaces* during any geological epoch received no deposit, and therefore the strata representing that epoch must be wanting there. Now, as there have been frequent oscillations of land-surfaces and sea-bottoms in past times, similar to those taking place at the present time, we find that in every known local series of strata there exist many and great gaps; so many and so great that the record may be regarded as only fragmentary. Such gaps are usually indicated by unconformity. It is the task of the geologist, by extensive comparison of rocks in all countries, to fill up these gaps, and make a continuous series. The leaves of the *book of Time* are scattered hither and thither over the surface of the earth, and it is the duty of the geologist to gather and arrange them according to their paging. This is done by *comparison* of rocks of different localities, partly by their lithological character, but principally by the fossils which they contain.

2. **Lithological Character.**—At the present time, in our seas and lakes, deposits are forming composed of sand, clay, mud, and lime, of every kind, in different localities. The same has taken place in previous epochs. Sandstones, limestones, and slates, not differing greatly from those forming at the present time, except in degree of consolidation, have been formed in every geological period. Lithological character, therefore, is no test of age. In comparing rocks of widely-separated localities, as, for example, the rocks of different continents, difference of lithological character is no evidence of difference of age, nor similarity of lithological character of any value in determining a geological horizon. But, as deposits are now being formed of a similar character over considerable areas, so also we find strata (the deposits of previous epochs), continuous and unchanged in lithological character, over large tracts of country. Therefore, in *contiguous* localities, similarity of lithological character becomes a very valuable means of identifying strata. Especially is this true if we find similar *groups* of strata. If, in two localities not too widely separated, we find a similar rock, e. g., a sandstone of similar grain and color, we conclude that they probably belong to the same age, or are, in fact, the same stratum.

3. **Comparison of Fossils.**—This is by far the *best*, and in *widely-separated localities the only*, method of determining the age of rocks. The principle of this method is that every geological epoch has its own fauna and flora with many *characteristic* forms, by which it may be identified everywhere in spite of those slight differences which result from geographical diversity; and, therefore, similarity of fossils shows similarity of age. There are, however, certain limitations to the application of this method which must be borne in mind:

(*a*) The lower marine species are much affected by depths and bottoms, and therefore we should expect that sandstone fossils, limestone fossils, and slate fossils, would differ in species even in the same epoch. Again, in lake and delta deposits, the entombed species would probably be entirely different from those of marine deposits. We must be careful, therefore, to compare fossils of rocks formed under similar conditions.

(*b*) We must also make due allowance for geographical diversity. This, as we have already stated, becomes greater and greater as we pass up the series of rocks. In the *lower* or older rocks the geographical diversity is small; in strata of the same age in different countries the fossils are quite similar, most of the genera and many of the species being undistinguishable. It is therefore comparatively easy, by comparison of fossils, to synchronize the strata and determine the geological horizon. In the *middle* rocks the geographical diversity is greater, but the general similarity is still considerable—the difference between organisms of consecutive epochs (geological faunas and floras) is still much greater than the difference between organisms of the same epoch in different countries (geographical faunas and floras); and, therefore, it is still quite possible, by comparison of fossils, to synchronize the strata. In the *higher* or newer rocks the geographical diversity has become so great that we are compelled to determine age and synchronize strata, no longer entirely by comparison of fossils of the different localities *with each other*, but also by the comparison of the fossils of each locality with the living species in the same locality. In these rocks we may determine relative age by relative percentage of living species, and similarity of age (geological horizon) by similarity of this percentage. In many cases, however, the age may be determined directly by means of characteristic fossils.

Manner of constructing a Geological Chronology.—The manner in which a geological chronology has actually grown up, under the combined labors of the geologists of all countries, may be briefly stated as follows: First, the *order of superposition*, and therefore the relative ages of the strata composing the rock-series of many different countries, were determined independently; next, by comparison of these, partly by *lithological character*, if the localities are contiguous, and *partly by fossils*, the geologist determines those which are synchronous and those which are wanting in each locality. Thus, out of several local series, by *intercalation*, he constructs a more complete ideal series. In case of doubt, he strives to find places where the doubtful strata come together, and observes their *relative position*. In Fig. 182, *A* and *B* represent two contiguous localities in which by independent study the relative positions and ages of 8 and 9 strata respectively have been determined. By comparison, the rocks of the two series are found to consist of fourteen strata of different ages, some being wanting in the one and some in the other locality.

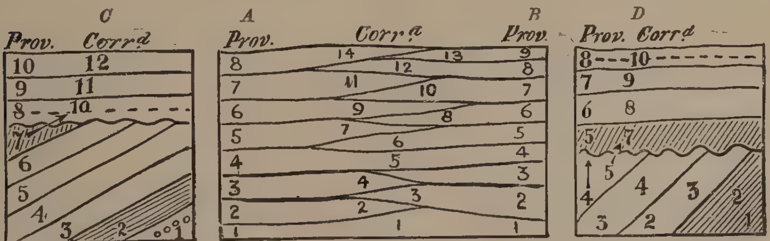

FIG. 182.—Diagram illustrating the Mode of determining the Chronological Order of Strata.

In this figure *A* and *B* represent conformable strata of contiguous localities and traceable throughout. In *C* and *D* we represent the more complex case of different countries and where unconformities occur. In *D* a series of 8 strata are provisionally made out, although it is known by the unconformity between 4 and 5 that there are some missing. In country *C* a series of 10 strata are first made out, although an unconformity is noted between 7 and 8. Now the comparison begins. First it is noted that 2 in the *C* series is identical with 1 of the *D* series. The *D* series is therefore corrected by making this 2 instead of 1, and all above are advanced accordingly as far as the unconformity. Then it is noted that what had been called 5 in the *D* series corresponds to 7 of the *C* series. Evidently 6 is wanting. The correction is made and the *D* series is completed to 10. Lastly, it is observed that what we had made 8 of the *C* series corresponds with 10 in the corrected *D* series, and that therefore 8 and 9 are wanting at *C*. The correction is made and the series completed to 12. Thus we make a complete series of 12, supplying number 6 from one locality and numbers 8 and 9 from the other. Thus as the examination of the earth's surface progresses, with every new country examined some gaps are filled up, and the series becomes more perfect. Many gaps still remain unfilled. The series will continue to be made more perfect, and the chronology more complete, until the geological examination of the earth-surface is finished. As knowledge becomes more complete the process becomes easier and more rapid. Characteristic forms often decide the question at once and elaborate comparison is resorted to only in case of doubt.

The second object to be attained by classification is the division and subdivision of the whole series into larger and smaller groups, corresponding to the eras, periods, and epochs of time. The principle on which this is done is as follows:

As we have already stated, the gaps in the series are usually indicated by unconformity. Now, since unconformity always indicates movements of the crust, changes of the outlines of sea and land, changes of climate, and consequent changes in the fauna and flora, these gaps mark the times of great revolutions in the earth's history, and are therefore the natural boundaries of the eras, periods, etc. The whole rock-series, therefore, is divided, by means of unconformity and the character of the fossils, into larger groups called *systems*, and these again into smaller groups called *series and formations*. The largest groups are founded upon universal, or almost universal, unconformity, and a consequent very great difference in character of organisms; the smaller groups are founded upon a less general unconformity and less difference in character of the organisms. Corresponding with the great divisions and subdivisions of the rock-system are the *eras*, *ages*, *periods*, and *epochs* of the history. The several terms expressing the divisions and subdivisions, both of the *rocks* and of the *history*, are unfortunately used in a loose manner. We will try to use them in the manner indicated. It will be observed that the divisions are founded upon (*a*) unconformity, and (*b*) change in fossils. These generally accompany each other, since they are produced by the same cause, viz., change of physical geography. In some localities, however, they may be in discordance. In this case, the change of fossils is considered the more important, and controls classification.

The following is an outline of the classification used in this work. Except in the uppermost part it is carried only as far as periods:

Eras.		Ages.	Periods.		Epochs.
5. Psychozoic.		7. Age of Man.	Human,	24	Recent.
4. Cenozoic.		6. The Age of Mammals.	Quaternary,	23	Terrace. Champlain. Glacial.
			Tertiary,	22	Pliocene. Miocene. Eocene.
3. Mesozoic.		5. The Age of Reptiles.	Cretaceous,	21	
			Jurassic,	20	
			Triassic,	19	
2. Palæozoic.	Upper.	*Carboniferous.* 4. The Age of Acrogens and Amphibians.	Permian,	18	
			Carboniferous,	17	
			Sub-carboniferous,	16	
		Devonian. 3. The Age of Fishes.	Chemung,	14	
			Hamilton,	13	
			Corniferous,	12	
			Oriskany,	11	
	Lower.	*Silurian.* 2. The Age of Invertebrates.	Helderberg,	10	
			Salina,	9	
			Niagara,	8	
			Trenton,	7	
			Canadian,	6	
		Cambrian.	Dikelocephalus zone,	5	
			Paradoxides zone,	4	
			Olenellus zone,	3	
1. Archæan, or Archæozoic.		1. Archæan.	Huronian,	2	
			Laurentian,	1	

CHAPTER III.

UNSTRATIFIED OR IGNEOUS ROCKS.

Characteristics.—The unstratified are distinguished from the stratified rocks, *a*, by the absence of true stratification—i. e., lamination of sorted materials; *b*, by absence of fossils; *c*, by a more or less crystalline or else a glassy structure; and, *d*, by their mode of occurrence explained below.

General Origin.—They have consolidated from a fused or semi-fused condition, and are, therefore, called *igneous rocks*. This origin is shown by their structure; by their occurrence in dikes and tortuous veins; by their effects on stratified rocks with which they come in contact; and by their resemblance in many cases to modern lavas. The question of their probable mode of origin will be more specifically treated after the description of their kinds.

Mode of Occurrence.—Igneous rocks occur, *a*, underlying the strata, and forming the great mass of the earth's interior; *a'*, forming the axes and peaks of nearly all great mountain-ranges; *bb'*, in vertical or nearly vertical sheets, filling great fissures in stratified or in other igneous rocks; *c*, in extensive horizontal sheets overlying the stratified country rock, as if outpoured on the surface; *c'*, lying conformably between strata, as if forced in a melted condition between them, or else outpoured on the bed of the sea and afterward covered with sediment; and, *d*, in tortuous veins connected with the great underlying masses. All these positions are illustrated in Fig. 183. In all these modes of occurrence the observed rock is connected with an underlying mass, of which it is but an extension.

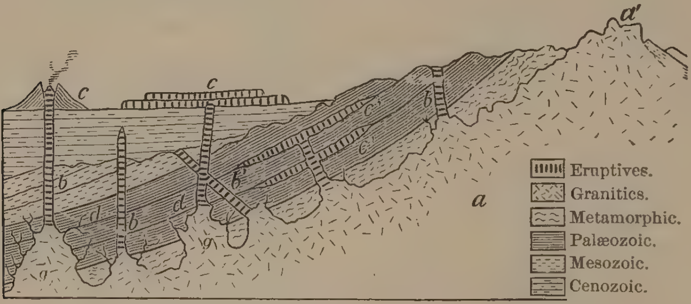

FIG. 183.—Diagram showing Mode of Occurrence of Igneous Rocks.

Extent on the Surface.—The appearance of these rocks on the surface is far less extensive than that of the stratified rocks. Certainly not more than one tenth of the land-surface is composed of them.

But, beneath, they are supposed to constitute the great mass of the earth.

Classification of Igneous Rocks.—Igneous rocks are best classified, not by means of their relative ages, but partly by their mineralogical character and partly by their mode of occurrence. By this method they most naturally fall into two primary groups—viz., the *Plutonic* or massive, and the *volcanic*, or true eruptive rocks. The rocks of the first group occur in great masses; those of the second group injected into fissures or outpoured on the surface. The former are *entirely* crystalline (holo-crystalline), and usually very *coarse-grained* (macro-crystalline); the latter are usually *finer grained* (micro-crystalline), or *imperfectly* crystalline (crypto-crystalline), or partly or even wholly *glassy*. The former seem to have solidified *in situ* (indigenous); the latter have been evidently *displaced* from their original position (exotic). The two groups, however, pass by insensible gradations into each other, so that the distinction is more or less artificial, and the same rock may sometimes be found in both groups.

I.—Plutonic or Massive Rocks.

General Appearance.—The rocks of this group are characterized by a coarse-grained, mottled, or speckled appearance, arising from the fact that they are composed of an aggregation of distinct crystals of different colors and of considerable size (macro-crystalline); and, what is much more important, the rock is usually *wholly made up of an aggregation of such crystals*, without any paste or ground-mass, either amorphous or glassy, between them.

The constituent minerals of this group are mainly quartz, feldspar, mica, and hornblende. In the speckled mass the opaque, white, or reddish or greenish crystals with glistening surface are feldspar, the transparent bluish glassy spots are quartz, and the black specks are usually hornblende. The mica can be easily detected as glistening scales of various shades.

Principal Kinds—Granite.—This rock, which may be regarded as the type of the group, consists of quartz, feldspar, and mica, or else of these, together with hornblende. Sometimes the mica and hornblende are wanting, and the quartz exists in the form of bent plates imbedded in feldspar, so that on cross-section they look like Hebrew or Arabic characters (Fig. 184, *A* and *B*). The rock is then called graphic granite, or *peg-*

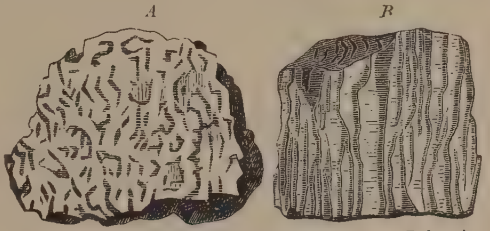

Fig. 184.—Graphic Granite: *A*, cross-section; *B*, longitudinal section.

matite. Sometimes the feldspar is in large, well-formed crystals in a finer but still crystalline ground-mass: then it is called *porphyritic granite.* Sometimes all the crystals are small, and the mass is evenly granular; then it is called *eurite*, or granulite.

Syenite.—English and many American writers use this term to designate a granitic rock in which mica is replaced by hornblende; and, when both hornblende and mica are present, they use the term *syenitic granite.* But on the Continent of Europe the term syenite is applied to a rock consisting essentially of feldspar and hornblende, and when, in condition, quartz is present (English syenite), they call the rock *quartz-syenite.* The general aspect of the rock is similar to granite.

In the rocks thus far mentioned the feldspar is an *orthic*, or *potash-feldspar* (*orthoclase*)—i. e., is a double silicate of alumina and potash.

Diorite.—This is a dark, speckled, greenish-gray rock, consisting of a crystalline aggregate of *clinic* or *soda-lime feldspar* (*plagioclase*), and *hornblende;* and, therefore, differs from syenite of German writers only in the form of the feldspar—viz., *plagioclase* instead of *orthoclase.* When quartz is present it is called quartz-diorite.

Diabase.—This is a dark, greenish crystalline rock, usually fine-grained, but sometimes granitoid, somewhat similar in appearance to diorite, but differing in the fact that *augite* replaces hornblende. It also often contains olivin. *Gabbro* is a granitoid variety of diabase, in which the augite takes the form of diallage.

We have selected these as good types of the groups; but they merge insensibly into each other, giving rise to many varieties, for the description of which we must refer the reader to special treatises on lithology.

Diorite and diabase are so frequently intrusive and fine-grained that they are often treated in an intermediate or even in the second group; but they also often occur massive.

Two Sub-Groups—Acidic and Basic.—Quartz is pure silicic acid. Feldspar is a silicate of alumina and alkali, with excess of silica—i. e., an *acid silicate* of these bases. In orthoclase the alkali is potash; in plagioclase, soda and lime. Moreover, the former is more acid than the latter. Hornblende and augite are *basic* silicates of somewhat similar composition. Augite is essentially a silicate of magnesia and iron; while, in hornblende, alumina and lime replace a portion of the magnesia. Remembering, futher, that quartz and feldspar are light-colored minerals, with specific gravity of about 2·6, while augite and hornblende are usually black minerals, with specific gravity of 3 to 3·5, it is plain that this group of rocks may be divided into two sub-groups, *acidic* and *basic*, often recognizable to the eye. In the one there is a predominance of quartz and feldspar, in the other of hornblende or augite. Also, in the one the feldspar is orthoclase, in the other plagioclase. The one is light colored, of less specific gravity, and more difficultly fusible; the other darker colored, heavier, and more easily fusible. Granite is the best type of the one; diorite, and especially diabase or gabbro, of the other. Syenite is intermediate. The percentage of silica, both free and combined, in granite is 62 to 81, and the specific gravity 2·6 to 2·7. The silica percentage in diabase is 45 to 56, and the specific gravity 2·7 to 2·9 (Von Cotta).

Mode of Occurrence.—True Plutonics, especially of the *granitic type*, such as granite and syenite, occur: 1. In large masses, forming the axes of great mountain-ranges, such as the Sierra and Colorado ranges (Fig. 185, *A*); or, 2. In rounded masses, appearing in the midst of stratified rocks like islands in the midst of the sea (Fig. 185, *B*); or, 3. Sometimes in tortuous, irregularly branching veins, extending only a little way from the great masses into the overlying stratified rocks, as if forced by pressure of superincumbent weight into small cracks of the latter (Fig. 183, *d*, Fig. 185, *A*, and Fig. 186, *A* and *B*). But rocks of more basic type, such as diorite and diabase, probably on account of greater fusibility, occur not only as Plutonics in massive form, but also as *intrusives* in dikes and intercalary beds, like true volcanics.

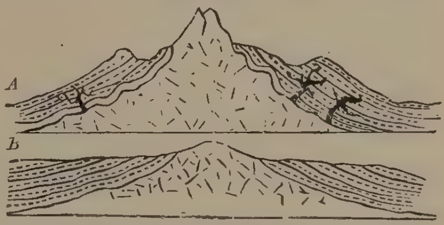

FIG. 185.—Diagram illustrating Mode of Occurrence of Granite.

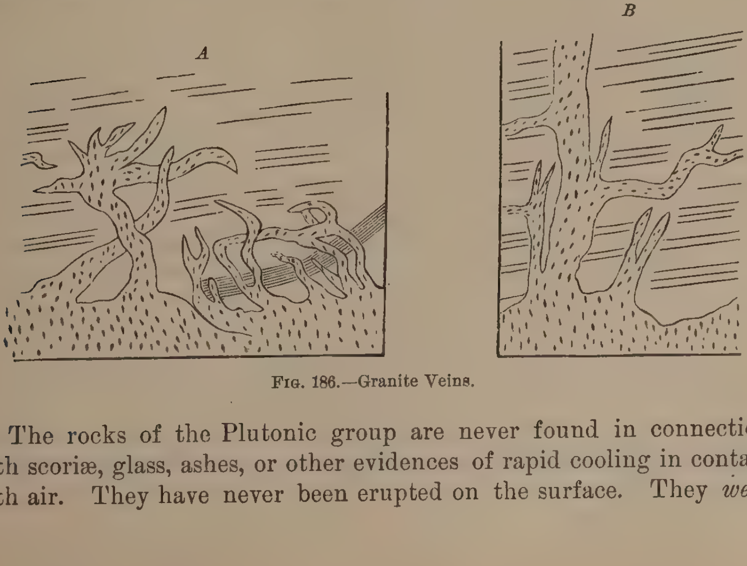

FIG. 186.—Granite Veins.

The rocks of the Plutonic group are never found in connection with scoriæ, glass, ashes, or other evidences of rapid cooling in contact with air. They have never been erupted on the surface. They *were* *cooled, and have solidified slowly under pressure in great masses and at great depths. Hence, when we find them at the surface, they have been exposed by extensive erosion.* They are either fused masses solidified without eruption (*a*), or they are the solidified reservoirs (*g*, Fig. 183) from which eruptions have come. In either case, they have themselves been cooled at great depths.

Intermediate Series.

Between the undoubted Plutonics, already described, and the undoubted volcanics, to be taken up hereafter, there is an intermediate series of rocks, which are sometimes placed in one group, sometimes in the other, and sometimes in a separate group, co-ordinate with the other two, and called *trappean* or *intrusive rocks.* They occur mostly in the older and middle rocks in the form of *dikes*, filling great fissures intersecting, or as intercalary beds between, the strata. If Plutonics are in great masses *beneath* the strata, and volcanics are outpoured masses *upon* the strata, these exist mostly as masses intruded *among* the strata. Again, if *Plutonics* are the great reservoirs and *volcanics* the outpoured liquid, the intrusives are the fillings of the conduits between. Erosion has subsequently carried away the overflowed portions, and exposed the conduits as dikes.

Kinds.—In the acidic groups, perhaps the most typical is *felsite.* This rock is a very compact, fine-grained aggregate of quartz and orthoclase, and therefore light-colored. Chemically it has the same composition as granite, and mineralogically it differs only in the fineness of texture and in the absence of mica. When the felsitic rock contains, imbedded in the fine-grained mass, large, well-formed crystals of feldspar, then it is called *porphyrite.* If quartz-crystals are also distinctly visible, then it is called *quartz-porphyry*, or *elvanite*, a mottled rock often mistaken for granite. The word *porphyritic* is often applied to any rock in which distinct crystals are visible in a finer ground-mass. Thus, we have porphyritic granite, porphyritic diorite, etc. The porphyritic structure is probably formed thus: The fused magma first cooled slowly until the large crystals separated; and then was injected into the fissure and the solidification completed.

Intrusive rocks of the basic sub-group are usually called *greenstones* or *traps.* This term, therefore, includes intrusive diorites, diabases, aphanites, melaphyrs, etc. These differ from the massive rocks of the same composition only by being finer grained: but the same is true also of felsites as compared with granites. The difference is probably wholly due to rate of cooling. The same fused mass which, if cooled slowly, forms granite, if injected into fissures and cooled more rapidly, would form felsite or quartz-porphyrite. The difference between massive and intrusive diorites is doubtless due to the same cause.

II.—Volcanic or Eruptive Rocks.

Texture and Appearance.—The rocks of this group are usually micro-crystalline, or even crypto-crystalline, and therefore in appearance are either minutely speckled or evenly grayish, of various shades. But the most important characteristic is, that they are not wholly crystalline, but consist either of crystals imbedded in an amorphous or glassy paste, or else are wholly amorphous or glassy. This texture shows that, as compared with the rocks of the other groups, they have *cooled quickly*, for, on account of the extreme viscosity of fused silicates (glass), complete crystallization can take place only by very slow cooling.

Physical Conditions.—All the physical conditions already described (p. 93) as characteristic of recent lavas, viz., the *stony*, the *glassy*, the *scoriaceous*, and the *tufaceous* conditions, are found abundantly in the more typical representations of this group.

Mineral Composition and Sub-Groups.—The most striking differences between the rocks of this and the other groups are found in their texture and mode of occurrence. Mineralogically the rocks of this group consist essentially of some form of feldspar, with hornblende or augite. Free quartz and mica, though sometimes present, especially the former, are neither necessary nor common. These also, like those of the other group, may be divided into two sub-groups, *acidic* and *basic*. In the one there is a predominance of orthic feldspar (sanidin); in the other, of either hornblende or augite and clinic feldspar (plagioclase). In true volcanics, as seen above, sanidin takes the place of orthoclase of the Plutonics. These, however, belong to the same group (orthoclase group), are equally acidic, and therefore have the same significance in lithology. The two sub-groups are, therefore, characterized by color, specific gravity, and fusibility, as already explained (p. 212), and, with some practice, can usually be distinguished in the field; though in many cases microscopic or chemical examination is necessary. The silica percentage of the extreme acidic type (rhyolite) is 70 to 82, and specific gravity 2·3 to 2·6; of the extreme basic (basalt) the silica percentage is 40 to 56, and specific gravity 2·9 to 3·1. The following schedule gives the most common and characteristic kinds under the two sub-groups:

VOLCANIC ROCKS.

	ACIDIC.	BASIC.
Stony condition.	Rhyolite. Liparite. Trachyte. Phonolite.	Basalt. Dolerite. Andesite.
Glassy condition.	Light-colored scoriæ. Pumice. Obsidian.	Black scoriæ. Tachylite.

IGNEOUS ROCKS.

		ACIDIC.			BASIC.	
II. Volcanic Rocks.	Occurring in overflows.	*Rhyolite.* Vitreous ground-mass. + × × Quartz. Orthoclase (sanidin).	*Trachyte.* Vitreous ground-mass. + × × Orthoclase (sanidin)	*Phonolite.* Vitreous ground-mass. + × × Sanidin, Nephelin.	*Andesite.* Vitreous ground-mass. + × × Plagioclase, Augite, or Hornblende.	*Basalt.* Vitreous ground-mass. + × × Plagioclase, Augite, Olivin.
I. Plutonic Rocks.	Occurring in intrusions.	*Quartz-porphyry.* Micro × × ground-mass. + × × Orthoclase, Quartz,		*Felsite.* Micro × × Orthoclase, Quartz.	*Diorite.* Same as below, but micro × ×	*Diabase.* Same as below, but micro × ×
	Occurring massive.	*Granite.* × × Quartz. Orthoclase, Mica.		*Syenite.* × × Orthoclase. Hornblende.	*Diorite.* × × Plagioclase. Hornblende	*Gabbro* × × Plagioclase, Augite, Olivin.

Principal Kinds.—In the acidic group the commonest and best type is *trachyte.* This is usually a light-colored rock, with a peculiar and very characteristic rough feel, due to microscopic vesicularity. It consists essentially of a ground-mass of orthic feldspar (sanidin) and augite, containing crystals of the former.

Rhyolite is similar in composition to trachyte, but contains a larger percentage of silica, and is very different in general appearance. It consists of a fluent, vitreous ground-mass or paste, usually containing crystals of sanidin, or even of quartz. When these crystals are conspicuous, so that the rock has a porphyritic appearance, it is called *liparite.* In some cases it may have even a granitoid appearance, and is then called *nevadite.* Such granitoid rhyolite may be easily distinguished from true granite by the presence of the glassy paste.

Phonolite is a light-grayish crypto-crystalline feldspathic rock, breaking or jointing in very characteristic thin tile-like slabs, which ring under the hammer (hence the name). It consists mainly of orthic feldspar (sanidin and nephelin).

In the *basic sub-group* the most common and typical is *basalt.* This is a very dark, almost black, crypto-crystalline rock, breaking with a dull, conchoidal fracture, and consisting essentially of microscopic crystals of plagioclase, augite, and olivin, in a glassy ground-mass of the same. Magnetite is also usually an abundant constituent. *Dolerite* has a somewhat similar composition, but lacks the olivin, and is more crystalline in structure, and therefore dark-grayish in appearance. *Andesite* is a dark-grayish rock, consisting essentially of plagioclase, with hornblende or augite. It is somewhat similar in color to dolerite, but is crypto-crystalline, like basalt, and often roughish to the feel, like trachyte. It has, therefore, been sometimes called trachydolerite.

All the rocks of both these sub-groups, but especially the more typical, have their scoriaceous and glassy varieties. These are the pumices and light-colored scoriæ and obsidians on the one hand, and the black scoriæ and tachylite on the other.

The table on preceding page is a condensed statement of the composition of the principal kinds in both primary groups, including also intrusives. The sign × × indicates crystals.

Modes of Eruption.—There have been in geological times two general modes of eruption. In the one the lavas have come up through *great fissures* formed by crust-movements and spread out as extensive *sheets;* in the other they have come up through *chimneys* and run off as *streams.* The one may be called *fissure-eruption*, the other *crater-eruption* or volcanoes proper. The one gives rise to extensive *lava-fields*, the other to *lava-cones.* The force of eruption in the one case is probably either the same as that which makes mountains—i. e., the lava is squeezed out by interior contraction of the earth, or else in some cases it may be hydrostatic—i. e., a *welling out* of a lighter liquid by the sinking of a heavier crust within it; the force, in the other case, is evidently the pressure of elastic gases, especially steam, as already explained (p. 97). We owe this distinction mainly to Richthofen, but it is now universally adopted in this country and quite generally in Europe. According to Richthofen, *primary* eruptions come always through great fissures and only at great intervals of time; afterward, surface-waters percolating through these fissure-erupted masses, still liquid within, give rise to *secondary* eruptions through craters. We have no examples of fissure-eruptions taking place at the present time, and therefore, in treating of igneous agencies in Part I, we spoke only of crater-eruptions. But it is impossible to explain the mode of occurrence of eruptives in the older rocks unless we admit eruptions in early geological times of a different kind from those occurring now in volcanoes.

Modes of Occurrence.—What we say under this head refers mainly to fissure-eruptions. True eruptive rocks occur: 1. As extensive vertical sheets filling *great* fissures which by subsequent erosion outcrop as great *dikes*, or else filling smaller radiating volcanic fissures as radiating volcanic dikes; 2. As sheets between the strata (intercalary beds) as if forced between the separated strata, or else outpoured on the bed of sea or lake, and again covered with sediments; 3. Outpoured on the land-surface as sheets or streams; 4. In the form of great dome-like masses on the surface or between the strata; and, 5. In the form of volcanic necks or plugs standing above the general level of the country.

Dikes.—The fillings of great fissures outcropping on land-surfaces are called *dikes*. They are very abundant in all the older stratified rocks, especially in mountain-regions. They vary in thickness from a few inches to fifty or one hundred feet; they may be traced over the country sometimes for many miles, even fifty or one hundred, and extend downward to great but unknown depths. Such dikes, outcropping over the face of the country, may be the exposed roots of ancient overflows which have been removed by subsequent erosion (Fig. 183, *b*); or they may be fillings of fissures which never reached the surface (Fig. 183, *b′*). In either case they are the evidence of extensive erosion. Sometimes the outcropping dike has resisted erosion more than the inclosing country rock, and the dike is left standing like a low, ruined wall running over the face of the country (Fig. 187, *a*); at other times the country rock has resisted more than the dike, and the place of the dike is marked by a slight depression, like a shallow ditch, or moat (Fig. 187, *b*).

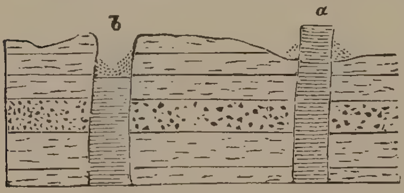

Fig. 187.—Dikes.

Effect of Dikes on the Intersected Strata.—The strata forming the bounding walls of a dike, or with which igneous rocks come in contact in any way, are almost always greatly changed by the intense heat of the fused matter. Limestones and chalk are changed into crystalline marble; clay is baked into porcelain-jasper, or even changed into schists; impure sandstones are changed into a speckled rock resembling gneiss; seams of bituminous coal are changed into anthracite, or sometimes into coke. In all cases the original stratification and the contained fossils are more or less completely destroyed. These effects extend sometimes only a few feet, sometimes many yards, from the dike.

Lava-Sheets.—Dikes outcropping on the face of the country, as already described, are doubtless in many cases the exposed roots of ancient overflows which have been removed by subsequent erosion, leaving only the *intruded* portion. But in more recent eruptions the overflow or *erupted* portions still remain. The fused matter has evidently come up through fissures and spread out as sheets, and often sheet after sheet has been successively outpoured forming layer upon layer (Fig. 188), until the whole surface of the country is deeply buried beneath the flood. The extent and thickness of the lava-fields thus formed are almost incredible. The great lava-flood of the Northwest covers Northern California, Northwestern Nevada, the greater part of Oregon, Washington, and Idaho, and extends far into British Columbia and Montana. Its extent is not less than 150,000 square miles, and its extreme thickness where cut through by the Columbia River is 3,000 to

4,000 feet. In another place seventy miles distant the Deschutes River cuts into the same lava-field, making a cañon 140 miles long and 1,000 to 2,500 feet deep, and has not yet reached bottom. At least thirty successive layers may be counted, one above the other, on the sides of this cañon. About a dozen volcanoes overdot this great surface. It is simply inconceivable that all this material came from these volcanoes. It evidently came up through great fissures in the Cascade, Blue Mountains, and Coast Range, and poured out on the surface, flooding the whole intervening country.* The Deccan lava-field, described by the Indian geologist,† is 200,000 square miles in extent, 2,000 to 6,000 feet thick, and entirely without detectable volcanic cones from which the lava could have come. These extensive fields are mostly of basalt. In Utah and Colorado, according to King and Endlich,‡ rhyolitic and trachytic lavas reach a thickness of 7,000 feet. As a general rule, outpourings of basalt reach the greatest extent, but each sheet is thin, as if the basalt had been *superfused;* while acidic lavas like trachyte and rhyolite are outpoured in very thick, sometimes dome-like masses, as if they had been only *semifused.*

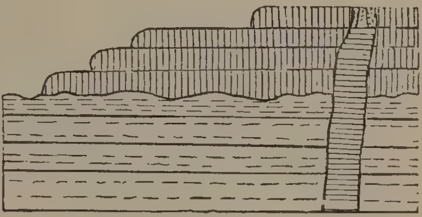

FIG. 188.—Lava-Sheets.

In basaltic lava-fields a remarkable step-like or terrace-like appearance is observable. The country seems to rise in successive tables or benches. From this has arisen the term *trap*, from the Swedish word *trappa*, a stair. This configuration is due to the abrupt terminations of the successive flows (Fig. 188).

Intercalary Beds and Laccolites.—Holmes, in Hayden's Report for 1875,# describes Mount Hesperus, Colorado, as wholly composed of stratified rocks (cretaceous), with intercalated beds of eruptives, as if the lava had forced itself between the strata. Such intercalary sheets, or *sills*, which have been often observed by others, probably pass by insensible gradations into *laccolites*—a new form of occurrence to which attention was first drawn by Holmes, but which has been elaborately described by Gilbert ‖ as characteristic of the Henry Mountains, and other groups in the Plateau region. In this case the liquid matter seems to have come up through fissures as usual, but, instead of breaking through to the surface, has lifted the upper strata and accumulated beneath in great dome-like masses which, in fact, constitute the bulk of the mountains (Fig. 189). The strata-covered dome thus formed is afterward eroded, and the igneous core or laccolite is exposed.

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* American Journal of Science, vol. vii, pp. 167, 259.

† American Journal of Science, vol. xix, p. 140, 1880. Manual of Indian Geology, p. 300 *et seq.*

‡ King, Geology of the Fortieth Parallel, vol. i, p. 632. Endlich, Hayden's Report for 1876, p. 112.

# Hayden's Report for 1875, p. 271.

‖ Gilbert, Geology of the Henry Mountains.

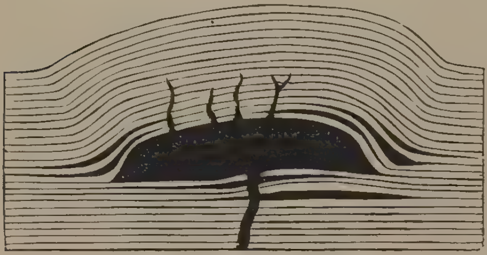

Fig. 189.—Laccolite (after Gilbert).

According to Gilbert, whether lava accumulates between the strata or outpours on the surface is merely a question of relative specific gravity. If the lava is lighter than the strata, then the latter will sink and the lava be outpoured. If, on the other hand, the surface strata be lighter than the lava, then the lava floats it up and accumulates beneath. It seems more probable, however, that it is rather a question of *liquidity* than of specific gravity. If the liquidity is perfect as in basalts, then it comes to the surface and outpours, and may extend to very great distances; but if, on the contrary, the lava is only a stiffly viscous, semi-fused mass, like trachyte and rhyolite, it may lift up the strata on its back in a dome. The quantity of lava accumulated is sometimes enormous. The Hiller laccolite, Henry Mountains, is equivalent to ten cubic miles.

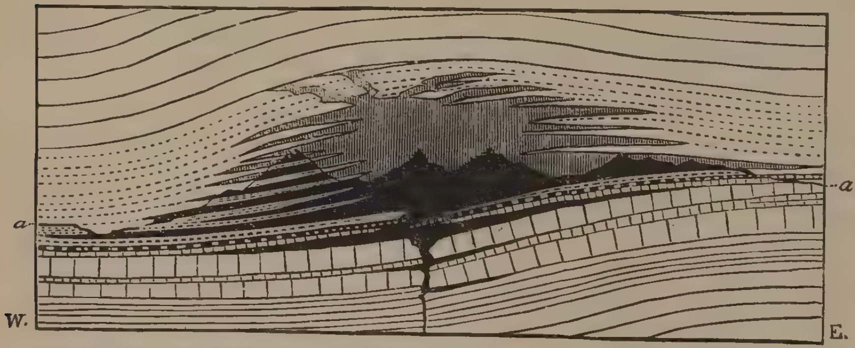

Fig. 190.—Ideal Cross-section of La Plata Mountain (after Cross). The irregular line, *a*, *a*, is the present surface.

The passage from intercalary beds to laccolites is well shown in Fig. 190, taken from Cross.

Volcanic Necks.—In the general erosion of a country the plugs which filled the interior of ancient volcanoes are often left, as more resistant remnants, standing above the general level of the country. These are called *volcanic necks.* Some examples are mentioned on p. 525. On account of the former frequent and long-continued fusion of these masses during repeated eruptions, their metamorphic effect on surrounding stratified rocks is far more profound and extensive than in the case of dikes.

Age—how determined.—When two dikes intersect each other, then, of course, the intersecting must be younger than the intersected dike. In this manner the *relative* age of dikes intersecting the same region may often be determined. The *absolute* age of igneous rocks can only be determined by means of the strata with which they are associated. If a dike is found intersecting strata of known age (*b*, Fig. 183), the dike must be younger than the strata. If a dike (*b′*), intersecting strata and outcropping on the surface, is found overlaid by other strata through which it does not break, then the igneous injection is younger than the former and older than the latter. The series of events indicated is briefly as follows: first, the older series of sediments has been formed; then fissures formed and filled by igneous injection; then erosion has carried away the upper portion of the strata and its included dike, so that the dike outcrops along the eroded surface; and, lastly, the whole has been submerged and again covered with sediment.

In the case of intercalary beds of igneous rocks, if the strata above and below are both metamorphosed by heat, then the fused matter has been forced between and is younger than the strata; if, however, the underlying stratum is changed but the overlying is not, then the igneous matter has been outpoured on the sea-bed and covered with sediment, and is, therefore, of the same age as the strata. The same principles determine the age of *sheets* and *streams.* If sheets are successively outpoured, one atop the other, then, of course, the order of superposition determines their relative age. So, also, if two streams run across each other, the overlying is the younger. In this way Richthofen and others have determined the order of succession of different kinds of tertiary eruptives. *Absolute* age, or the geological time of eruption, can only be determined by the age of the associated strata.

Of Certain Structures found in many Eruptive Rocks.

Columnar Structure.—Many kinds of eruptive rock exhibit sometimes a remarkable columnar structure. This is most conspicuous in basalt, probably because this rock has been superfused, and is therefore sometimes called basaltic structure. Sheets and dikes of this rock are often found composed wholly of regular prismatic jointed columns, closely fitting together, varying in size from a few inches to a foot or more, and in length from several feet to fifty or one hundred feet. When these columns have been well exposed on cliffs by the action of waves, or on river-banks by the erosive action of currents, or even by atmospheric disintegration, they produce a very striking scenic effect (Figs. 191, 192). In Europe the Giant's Causeway, on the coast of Ireland, and Fingal's Cave, in the island of Staffa on the west coast of Scotland, are conspicuous examples. In the United States we have examples in Mount Holyoke, on the Connecticut River; in the Palisades of the Hudson River; in the traps on the shores of Lake Superior; and especially in splendid cliffs of the Columbia and Deschutes Rivers, in Oregon.

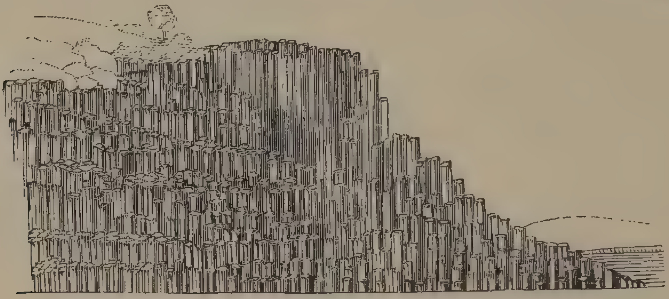

Fig. 191.—Columnar Basalt, New South Wales (Dana).

Direction of the Columns.—The direction of the columns is usually at right angles to the cooling surface. In horizontal sheets, therefore, the columns are vertical, but in dikes they are horizontal (Fig. 193). A dike left standing above the general surface of country sometimes presents the appearance of a long pile of cord-wood. In some cases the columns are curved and twisted in a manner not easy to explain; sometimes, instead of columnar, a *ball*-structure is observed.

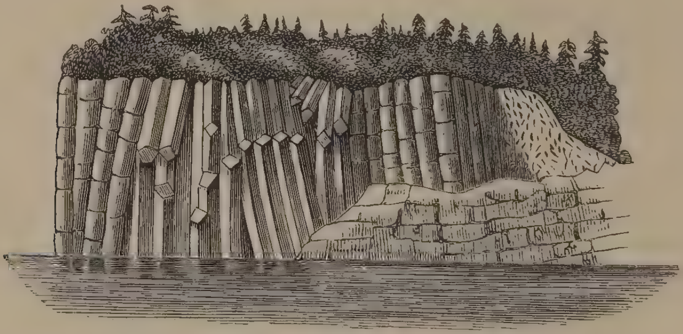

Fig. 192.—Basaltic Columns on Sedimentary Rock, Lake Superior (after Owen).

Cause of Columnar Structure.—There is little doubt that this structure is produced by contraction in the act of cooling. Many substances break in a prismatic way in contracting. Masses of wet starch, or very fine mud exposed to the sun, crack in this way. In basalt the structure is more regular than in any other known substance. The subject of the cause of jointed columnar structure has been very ably discussed by Mr. Mallet.*

Volcanic Conglomerate and Breccia.—If a stream of fused rock, whether from a crater or a fissure, run down a stream-bed, it gathers up the *pebbles* in its course, and after solidification forms a conglomerate which differs from a true conglomerate (p. 179) in the fact that the uniting paste is igneous instead of sedimentary. In a similar manner volcanic breccias are formed by the flowing of a lava-stream over a surface covered with angular fragments or *rubble.* Breccias and tufas are also formed by cementation of cinders and ashes accumulated about volcanic vents.

The disintegration of volcanic rocks, and their transportation and deposit, will of course give rise to *aqueous* conglomerates and breccias composed of volcanic materials, which often are difficult to distinguish from true volcanic conglomerates and breccias. These aqueous conglomerates and breccias of volcanic material pass by insensible gradations into tufas, which, as already explained (p. 93), consist of fine volcanic material cemented into an earthy mass and often sorted by water.

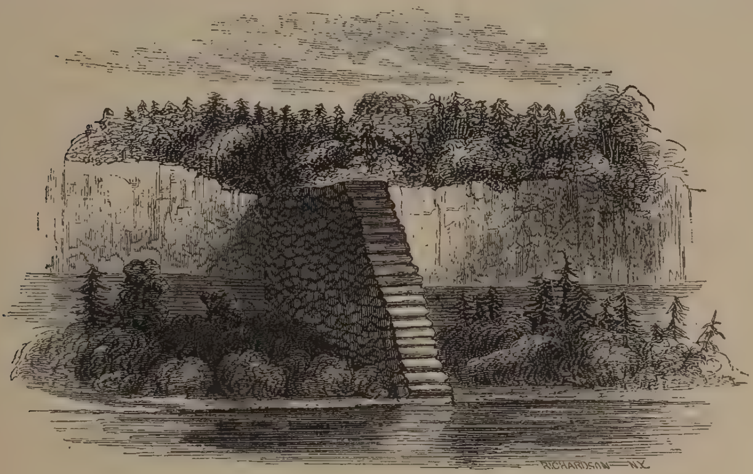

Fig. 193.—Columnar Dike, Lake Superior (after Owen).

Amygdaloid.—Still another structure, very common in lavas and traps, is the amygdaloidal. The rock called amygdaloid (Fig. 194) greatly resembles volcanic conglomerate, being apparently composed of almond-shaped pebbles in an igneous paste, but is formed in a wholly different way. Outpoured traps, and especially lava-streams, are very often vesicular—i. e., filled with vapor-blebs, usually of a flattened, ellipsoidal form. In the course of time these cavities are filled with silica, carbonate of lime, or some other material, by infiltrated water holding these matters in solution. Sometimes the filling has taken place very slowly by successive additions of different-colored material. Thus are formed the beautiful agate pebbles, or more properly *amygdales*, so common in trap. The most common filling is silica, because water percolating through igneous rocks is always alkaline, and holds silica in solution.

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* Philosophical Magazine, August and September, 1875.

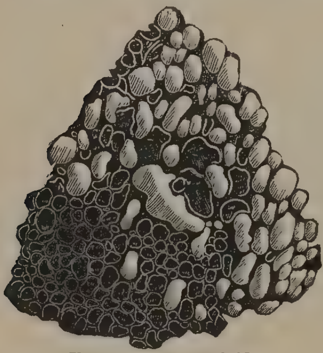

FIG. 194.—Amygdaloid.

SOME IMPORTANT GENERAL QUESTIONS CONNECTED WITH IGNEOUS ROCKS.

1. *Other Modes of Classification.*

There is no subject connected with geology which is in a state of greater confusion than the classification and nomenclature of igneous rocks. It seems proper, therefore, to mention some of the different views entertained.

Many geologists think that igneous rocks may be thrown into three groups, characteristic of different periods of the earth's history, and which, therefore, are now found associated with the stratified rocks of different ages. These are: 1. The granitic group, including granites and syenites, associated with Archæan and Palæozoic rocks; 2. The trappean group, including diorites, porphyry, dolerite, etc., associated with the later Palæozoic and the Mesozoic rocks; and, 3. The volcanic rocks, including basalts, trachytes, etc., associated with the Tertiary rocks. They think, therefore, that the earliest eruptions were granitic, then trappean, and lastly volcanic. Furthermore, they think that the first have come up mostly in great, dome-like masses; the second, mostly intrusive, in dikes and fissures; and the third through craters forming volcanoes.

Again, many think that erupted matters, of different times, have become progressively *more basic.* They think that, although each group may be divided into a more acidic and a more basic sub-group, yet, as a whole, the granitic group is the most acidic and the volcanic the most basic, the trappean being intermediate, as shown in the accompanying diagram.

Again, these two views, which are usually held by the same persons, are by them connected with a third view, in regard to the original constitution of the earth's crust. On first cooling, the outer layer is supposed to have been highly oxidized, highly siliceous, and therefore comparatively light—in other words, *granitic;* beneath this was a less oxidized, less acid layer, and so on progressively, the deeper layers becoming heavier and heavier, and more and more basic. The first eruptions were from the outer layer, and therefore granitic. Afterward, as the crust grew thicker and thicker, the eruptions were from deeper and deeper layers, and therefore denser and denser, and more and more basic.

BASIC.

Acidic.	Basic.
Volcanic.	
Rhyolite.	Basalt.
Trappean.	
Quartz-Porphyry.	Diabase.
Granitic.	
Granite.	Gabbro.

ACID.

But, in answer to these views, it may be said that, as to *age*, there can be no doubt that granite, though most commonly associated with the older rocks, is found in strata of all ages up to the middle Tertiary, and fissure eruptions have occurred in all ages up to the latest Tertiary. The granite of Mont Blanc was pushed up at the end of the Eocene (Lyell), and the great fissure-eruptions of the Northwest took place at the end of the Miocene and during the Pliocene. On the other hand, basalts are found in pre-Cambrian rocks (Walcott).* Also, as to *composition*, rhyolite and liparite have much the same chemical composition as granite, except that more of the silica is in *combination* and less of it *free* in the former than in the latter. Some early diorites and gabbros have much the same chemical (if not mineralogical) composition as basalt.

Again, others, with much reason, think that all the differences between the three groups in mineralogical character and crystalline structure are due wholly to the different depths at which and the slowness with which solidification took place. They think, therefore, that if trachyte or rhyolite (Fig. 183, *c*) could be traced downward deep enough it would pass into porphyry (*b*), and finally into granite (*g*), and similarly basalt would pass into dolerite and diorite, and finally into olivin-diabase or gabbro.† On this view, what *we* can not do, has been done for us by *erosion;* and granite is most commonly associated with older rocks only because these have been most eroded, and therefore their deeper parts, or even the fountain-reservoirs from which eruptions have come, have been exposed. Similarly, a less extreme erosion of the Mesozoic rocks has exposed the porphyritic and dioritic dikes through which eruptions came up; while, of the modern lavas, only the upper or overflowed parts are exposed. This view explains completely all the phenomena of igneous rocks, and the gradations between them, in chemical and mineralogical composition and in crystalline structure and is therefore very probably true. We have substantially assumed it in the preceding descriptions.

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* American Journal of Science, vol. vii, p. 167, 1874.

† This gradual change has very recently been distinctly observed in Southeastern Europe by Judd (Geological Magazine, 1876, vol. xxxii, p. 292), and also in Colorado by Peale (Hayden's Report for 1873, p. 261), and also by Hague and Iddings in Nevada (United States Geological Survey Bulletin, No. 17, 1885).

The confusion in the classification and nomenclature of igneous rocks is still further increased by the undoubted fact that many of the kinds of rocks mentioned above as igneous are found also among metamorphic rocks which have never been erupted at all. This subject is further treated under the head of Metamorphism (p. 230 *et seq.*).

2. *Richthofen's Classification of Tertiary Eruptives.*

By far the most noted attempt to classify by age, or to correlate the kinds of igneous rocks with their ages, is found in Richthofen's classification of Tertiary eruptives. According to Richthofen, there is a regular and invariable order of succession among the eruptive rocks of Tertiary times; the order being—1. Propylite.* 2. Andesite. 3. Trachyte. 4. Rhyolite. 5. Basalt. This order, however, applies only to *primary or fissure eruptions;* for, since primary erupted masses may become the seats of subsequent secondary or crater eruptions, it is evident that secondary eruptions of a lower group may be synchronous with primary eruptions of a higher group.†

These views of Richthofen's have attracted wide attention, but have not been generally confirmed. All that is as yet generally accepted in regard to the order of Tertiary eruptives is that the trachytes (including in this term with the trachytes proper also the andesites and the rhyolites) precede the basalts.

Dutton and Iddings find in successive eruptions in the same place a law of differentiation from a generalized type like andesite into more and more specialized acid on the one hand and basic on the other. Judd also, in his work on Volcanoes, admits that an intermediate type like andesite (propylite is usually regarded as a variety) is first erupted, then an acid type like trachyte and rhyolite, and last basalt. He accounts for this by supposing a homogeneous fused mass (such as would be formed by fusion of many different kinds of strata) to be first erupted as soon as formed. This would make an intermediate type. The remainder of the fused mass after long standing would separate into a lighter acid portion above and a heavier basic portion below. These would, therefore, be successively erupted as rhyolite and basalt. On the other hand Geikie and Teall find a law of increasing acidity, and Brögger * confirms this law, but only for plutonics.

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* Propylite is regarded by many as an altered andesite.

† Richthofen's Natural History of Volcanic Rocks, Memoirs of California Academy of Science, vol. i, Part II.

3. *General Origin of Igneous Rocks.*

The fused matter outpoured on the surface or intruded among the stratified rocks may be derived from the original fused magma of the primal incandescent earth either universal within or left as local remnants in the solidification of the earth's shell, and never having been consolidated before eruption. Many geologists take this view. But it is not improbable that they may result from local fusion of stratified rocks or refusion of previously consolidated igneous rocks, and that we look in vain for any examples of the original magma. This question may be regarded as still undecided.

4. *Origin of the Various Kinds of Eruptive Rocks by Differentiation of Rock Magmas.*

Until very recently it was taken for granted that a fused mass would have the same composition throughout and would retain such composition until solidified, and therefore that all eruptions in the same place and from the same magma must have the same composition, chemical if not mineral. When, therefore, diverse species from extreme acid to extreme basic were found in the same locality it was supposed that they came from eruptions at different times and from different magmas, and many ingenious attempts have been made to classify these according to their supposed relative ages. The most celebrated of these attempts is that of Richthofen in the classification of Tertiary eruptives, given above. But now it has been definitely proved, especially by the observations of Iddings on the eruptives of Electric Peak and Sepulchre Mountains, Montana, that the same molten mass in the act of cooling differentiates into basic kinds on the one hand and acid kinds on the other. Speaking in a general way, it may be said that in the gradual cooling of such a mass the first to crystallize are the more basic minerals. These crystallize first in the *outlying parts* when the cooling is most rapid, and then similar materials continue to accumulate and crystallize there by *migration* of the more basic materials to the solidifying parts, leaving a more acid remnant in the center to solidify last. It is true that this is contrary to what we would expect if we regard only the relative fusibilities of the several minerals, for the basics are the more fusible and therefore ought to be the

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* Eruptivegesteine des Kristianiagebietes. Eruptivegesteine bei Predazzo, 1895.

last to *solidify*. But we must regard all the minerals as *in solution* in a fused magma of alkaline silicates, and the basic minerals as the more *insoluble* and therefore as *crystallizing* first. Thus the phenomena of the origin of different species from a single fused mass may be explained by (1) the tendency to differentiate on cooling; (2) the greater insolubility of the more basic minerals, and therefore their earlier crystallization in the outer parts; and (3) the *migration* of materials to the point of crystallization. Add to this the fact that different original magmas differ in composition, and all the different kinds of eruptives receive a ready explanation.

CHAPTER IV.

METAMORPHIC ROCKS.

THERE is a third class of rocks, intermediate in character between the ordinary sedimentary and the igneous rocks, and therefore put off until these had been described. The rocks of this class are stratified, like the sedimentary, but crystalline, though never glassy, and usually non-fossiliferous, like the igneous rocks. They graduate insensibly on the one hand into the true unchanged sediment, and on the other into true igneous rocks of the granitic type.

Origin.—Their origin is evidently sedimentary, like other stratified rocks, but they have been subsequently subjected to heat and other agents which have changed their structure, sometimes entirely destroying their fossils and even their lamination structure, and inducing instead a crystalline structure. The evidence of their sedimentary origin is found in their gradation into unchanged fossiliferous strata; the evidence of their subsequent change by heat, in their gradation into true igneous rocks. For this reason they are called *metamorphic* rocks.

Position.—All the lowest and oldest rocks are metamorphic. The converse, however, viz., that metamorphic rocks are always among the oldest, is by no means true. Metamorphism is not, therefore, a test of age. Metamorphic rocks are found of all ages up to the Tertiary. The Coast Range of California is much of it metamorphic, although the strata belong to the Tertiary and Cretaceous periods. Metamorphism seems to be *universal* in the Laurentian, is *general* in the Palæozoic, *frequent* in the Mesozoic, *exceptional* in the Tertiary, and entirely *wanting* in recent sediments. It is therefore less and less common as we pass up the series of rocks. The *date* of metamorphism is also different from that of the origin of the strata. Metamorphism has taken place in all geological periods, and is doubtless now progressing in deeply-buried strata.

Metamorphism is also generally associated with foldings, tiltings, intersecting dikes, and other evidences of igneous agency, and is therefore chiefly found in mountainous regions. It is also usually found only in very *thick strata.*

Extent on the Earth-Surface.—These rocks exist, outcropping on the surface, over wide regions. Nearly the whole of Canada and Labrador, a large strip on the eastern slope of the Appalachians, and a large portion of the mountainous regions of the western border of this continent, are composed of them. Beneath the surface they probably underlie all other stratified rocks, and are therefore the most widely diffused of all rocks. Their thickness is also often immense. The Archæan series of Canada is probably 50,000 feet thick, and metamorphic throughout.

Principal Kinds.—The principal kinds of metamorphic rocks are: *Gneiss*, *mica-schist*, *chlorite-schist*, *talcose-schist*, *hornblende-schist*, *clay-slate*, *quartzite*, *marble*, and *serpentine.*

Gneiss, the most universal and characteristic of these rocks, has the general appearance and mineral composition of granite, except that it is more or less distinctly stratified. Often, however, the stratification can only be observed in large masses. *Gneiss* runs by insensible gradations, on the one hand, into granite, and on the other, through the more perfectly stratified schists, into sandy clays or clayey sands.

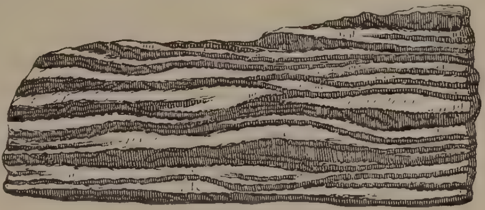

FIG. 195.—Gneiss.

The *schists* are usually grayish fissile rocks, made up largely of scales of *mica*, or *chlorite*, or *talc.* Hornblende-schist is similarly made up of scales of hornblende, and is therefore a very dark rock. The fissile structure of schists is due to the presence of these scales, and is therefore wholly different from that of *slates.* It is called *foliation-structure.*

Serpentine is a compact, greenish magnesian rock. The other varieties need no description. Hornblende-schists run by insensible gradations into clay-slates on the one hand, and into diorites and syenites on the other.

All these kinds may be regarded as changed sands, limestones, and clays, the infinite varieties being the result of the difference in the original sediments and the degrees of metamorphism. Sands and limestones are often found very pure; such when metamorphosed produce quartzite and marble. Clays, on the contrary, are almost always impure, containing sand, lime, iron, magnesia, etc. Such impure clays, if sand is in excess, produce by metamorphosis gneiss, mica-schist, and the like; but if lime and iron are in considerable quantities they produce hornblende-schist or clay-slate; if magnesia, talcose-schist. The origin of serpentine is not well understood; but it is evidently in many cases a changed magnesian clay. All gradations between such clays and serpentine may be found in the Tertiary and Cretaceous strata of the Coast Range of California. But it is also often, perhaps oftenest, a changed igneous rock containing much olivin (peridotite).

Theory of Metamorphism.

There are few subjects more obscure than the cause of metamorphism, and the conditions under which it occurs. Some important light has been thrown on it, however, recently. For the sake of clearness, it will be better to divide metamorphism into two kinds, somewhat different in their causes, viz., *local* and *general.*

Local Metamorphism is that produced by direct contact with evident sources of intense heat, as when dikes break through stratified rocks. As already seen (p. 218), under these circumstances, impure sandstones are changed into schists, or into gneiss; clays into slates, or into porcelain jasper; limestones, into marbles; and bituminous coal, into coke, or into anthracite. In these cases it is evident that the cause of the change is the intense heat of the incandescent, fused contents of the dike at the moment of filling. In such cases of local metamorphism, the effects usually extend but a few yards from the wall of the dike.

General Metamorphism.—But in many cases we can not trace the change to any evident source of intense heat. Rocks thousands of feet in thickness, and covering hundreds of thousands of square miles, are universally changed. The principal agents of this general metamorphism seem to be *heat*, *water*, *alkali*, *pressure* with folding and shearing.

That *heat* is a necessary agent is sufficiently evident from the general similarity of the results to *local* metamorphism. But that the heat was not intense, and therefore not sufficient of itself to produce the effects, is also quite certain. For (*a*) metamorphic rocks are often found interstratified with unchanged rocks.* Intense heat would have affected them all alike, or nearly alike. (*b*) Many minerals are found in metamorphic rocks which will not stand intense heat. As an example, carbon has been found in contact with magnetic iron-ore, although it is known that this contact can not exist, even at the temperature of red-heat, without reduction of the iron-ore. (*c*) The effect of simple dry heat, as shown in cases of local metamorphism, does not extend many yards. (*d*) *Water-cavities* are found abundantly in metamorphic rocks. This will be more fully explained farther on.

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* American Journal of Science, vol. xxi, p. 327, 1881.

Water.—Heat combined with water seems to be the true agent. Recent experiments of Daubrée, Senarmont, and others, prove that water at 400° C. (=752° Fahr.) reduces to a *pasty condition* nearly all ordinary rocks; moreover, that at this temperature crystals of quartz, feldspar, mica, augite, etc., are formed. In fact, as Guthrie has shown (Geological Magazine, vol. vi, p. 244, 1889), there are all gradations between *solution* and true igneous fusion through various grades of hydrothermal fusion. Such a pasty or aqueo-fused mass slowly cooled would form a crystalline rock containing crystals of quartz, feldspar, mica, etc; in other words, would be metamorphic. The quantity of water necessary for these effects is shown by experiment to be very small—only five to ten per cent. In other words, *the included water of sediments is amply sufficient.*

Alkali.—Alkaline carbonates, or alkaline silicates, so common in natural waters, greatly promote the process, causing the aqueo-igneous pastiness or aqueo-igneous fusion to take place at a much *lower temperature.*

Pressure with Shearing.—*Pressure* is a necessary condition of the existence of high temperature in the presence of water, and is thus an *indirect* agent of metamorphism, but it is also a *direct* agent; since it increases chemical action of many kinds, and therefore *solubility*, and also increases the heat by *shearing.*

It is evident, therefore, that while metamorphism by dry heat would require a temperature of 2,000° to 3,000° Fahr., in the presence of water the same result is produced at 572° to 752° Fahr. (300° or 400° C.); or in the presence of alkali, even in small amount, probably at 300° or 400° Fahr.

Application.—All these agents are found associated in deeply-buried sediments. Series of outcropping strata are often found 20,000 or even 40,000 feet thick. The lower strata of such a series by the regular increase of interior heat alone must have been, before uptilting, at a temperature of between 700° and 800° Fahr., a temperature sufficient, with their included water, to produce complete aqueo-igneous pastiness, and therefore, by cooling and crystallization, complete metamorphism.

Suppose, then, *a*, *sb*, Fig. 196, represent the contour of land and sea-bottom at the beginning of any period, and the dotted lines the isogeotherm of 400° and 800°. If, now, sediments 40,000 to 50,000 feet thick be deposited so that the sea-bottom is raised to *s′ b′*, then the isotherm of 800° will rise to the position of the broken lines and invade the lower portions of the sediments with their included water.

Such sediments would be completely changed in their lower portions, and to a less extent higher up. It is probable that even 300° to 400° Fahr. is sufficient to produce a considerable degree of change; or even 200°, if alkali be present.

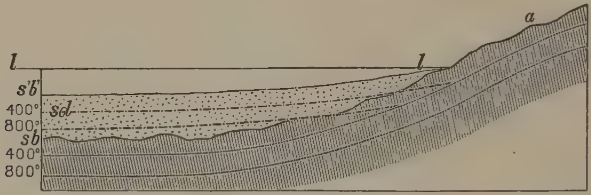

Fig. 196.—*sb*, original sea-bottom; *s'b'*, sea-bottom after sediments, *sd*, have accumulated: . . ., isogeotherms of 800° and 400°: —.—.—, same after accumulation of sediments.

Crushing.—Although simple gravitative pressure is only a condition, and not a cause, of heat, *horizontal pressure with crushing* and folding of the crust, by the conversion of mechanical energy into heat, becomes, as Mallet has shown,* an active source of this agent. Now, in all cases of metamorphism we find ample evidences of such horizontal crushing in the associated foldings and cleavage of the strata.

Mechanical Metamorphism.—Very recently it has been shown that lateral pressure with crushing and shearing, and sometimes even a kind of flowing of the crushed rock, will produce a schistose structure not only in stratified but even in igneous rocks. This has been called *mechanical or dynamical metamorphism.* Thus the difficulty of determining the origin of metamorphic rocks becomes still greater.

Again, percolating water containing silica, even at *ordinary* temperature and pressure, but especially at high temperature under heavy pressure, may often fill up by crystallization the interstices of a sand-rock so as to make a perfect quartzite.†

Explanation of Associated Phenomena.—This theory readily explains—1. Why metamorphism is always associated with great thickness of strata; 2. Why the oldest rocks are most commonly metamorphic, since these have usually had the newer rocks piled upon them, and have been subsequently exposed by erosion. The newer rocks are sometimes also metamorphic, but in these cases they are *very* thick. 3. It also explains the interstratification of metamorphic with unchanged rocks; since some rocks are more easily affected by heated water than others, and the composition of the included water may be also different, some containing alkali and some not. 4. It also explains its association with foldings of strata and with mountain-chains, as will be more fully explained hereafter.

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* Philosophical Transactions, 1873, p. 147.

† Irving, American Journal, vol. xxv, p. 402, 1883, and vol. xxxi, p. 225, 1886.

If metamorphism is only produced in deeply-buried sediments, then the exposure of such rocks on the surface can only result from extensive erosion.

Origin of Granite.

No doubt most granites are the consolidated reservoirs from which eruptions have come; but there is much reason to believe that at least some granites are not the result of simple dry fusion, as is usually supposed; but, on the contrary, only *the last term of metamorphism of highly-siliceous sediments*, and have not given rise to eruptions at all. According to this view, incipient pastiness by heat and water makes gneiss; complete pastiness, completely destroying stratification, makes granite. The principal arguments for this view may be briefly stated as follows: *

1. In many localities in mountain-regions, and nowhere better than in the Sierra of California, every stage of gradation may be observed between clayey sandstones and gneiss, and between gneiss and granite. So perfect is this gradation, that it is impossible to draw sharply the distinction. Even geologists who believe that granite is *the primitive* rock have been compelled to admit that there is also a metamorphic granite, scarcely distinguishable from primitive granite.

2. Not only gneiss, but even granite, is sometimes interstratified with undoubted sedimentary rocks.†

3. Chemists recognize two kinds of silica, viz., an amorphous variety of specific gravity 2·2, and a crystallized variety (quartz), specific gravity 2·6. These two varieties differ from each other not only in density, but also in chemical properties, the former being much more easily attacked by alkalies than the latter. By solidification from fusion (dry way) only the variety of specific gravity 2·2 has been artificially formed, while the variety 2·6 is formed only by slow deposit from solution (humid way).‡ Now, the silica of granite is always of the variety 2·6, and therefore was probably formed in presence of water.

4. Crystals of quartz, hornblende, and mica, are frequently formed in Nature by the humid process, as, for example, in metamorphic rocks; and have also been *artificially* formed by the same process by Daubrée, Senarmont, and others, as already stated (p. 231); but they have never been formed artificially by the dry way.

5. In nearly all rocks and minerals microscopic cavities are found indicating the conditions under which crystallization or solidification

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* Rose, Philosophical Magazine, xix, p. 32; Delesse, Archives des Sciences, vol. vii, p. 190; Hunt, American Journal of Science and Arts, new series, vol. i, pp. 82, 182.

† Dana, American Journal of Science, vol. xx, p. 194, 1880.

‡ Recently quartz, specific gravity 2·6, has been formed under peculiar conditions by dry fusion (American Journal of Science, vol. xvi, p. 154, 1878).

took place. If crystals are formed by sublimation, they contain *vacuous* cavities. If they are formed by solidification from fusion (dry way), and if gases or vapors are present, they may contain vapor-blebs; but, if they crystallize slowly from a glassy magma, they contain spots of glassy matter, or *glass cavities* or inclusions, as in slags and lavas. If they are formed by crystallization from solution, then they have *fluid cavities*, or liquid inclusions, as they are now usually called. Now, not only are these fluid cavities found in metamorphic rocks, but also in the quartz and feldspar of granite. "A thousand millions of these microscopic cavities in a cubic inch is not at all unusual; and the inclosed water often constitutes one to two per cent of the volume of the quartz."* These facts point plainly to the agency of water in the formation of at least some granite. Among the liquids thus inclosed in granite and other metamorphic rocks is often found *liquid carbonic acid.* This fact shows the great pressure under which solidification of the rock took place.

Even the temperature at which metamorphic rocks and granite solidified has been approximately determined by Mr. Sorby. The principle on which this is done is as follows: If crystallization from solution, or solidification in the presence of water, take place at *ordinary* temperatures, then the fluid cavities will be full; but if at high temperatures, and the mass subsequently cools, then by the contraction of the contained liquid more than of the containing walls; a *vacuous* space will be formed which will be larger in proportion to the amount of contraction, and therefore to the temperature of solidification. Knowing, therefore, the relative sizes of the vacuole and the contained water, and the coefficient of expansion of the water and the rock, the temperature at which the cavity would fill (which is the temperature of solidification) may be calculated. Sometimes this temperature may be gotten by actual experiment, i. e., by heating until the cavity fills. By this method Mr. Sorby has determined the temperature of solidification of certain metamorphic rocks of Cornwall as 392° Fahr., and of some granites as 482°, and other only 212°.

It seems almost certain, therefore, that some granites have not been formed by dry, igneous fusion. Yet that this rock has been in a liquid or pasty condition is perfectly certain from its occurrence in tortuous veins. Therefore it has been rendered pasty by heat in the presence of water under great pressures, such as always exist in deeply-buried strata. The weight of the superincumbent strata, or else pressure by folding and crushing of the strata, has forced it into cracks and great fissures.

What we have said of granite applies of course to the whole granitic group. Granitic rocks are often only the last term of the metamorphism of sediments; granite being produced from the more siliceous sediments, and diabase and gabbro from the more basic impure clays. But we can not stop with this group. It is probable that many if not all the rocks of the Trappean group also may be made by metamorphism of sediments. Many bedded diorites, dolerites, and felsites, are undoubtedly formed in this way, for the gradations can be distinctly traced into slates. Prof. Dana* has recognized this as so certain that he proposes the addition of the prefix *meta* to these to indicate their origin. Thus he recognizes a syenite and a metasyenite, a diorite and a metadiorite, dolerite and metadolerite, felsite and metafelsite, etc., and we might add granite and metagranite.

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* Sorby, Quarterly Journal of the Geological Society, vol. xiv, pp. 329, 453.

Many geologists push these views so as to include also even the true lavas. Deeply-buried sediments under gentle heat in the presence of water and pressure undergo incipient change and form metamorphic rocks; under greater heat become pasty and form granite, metasyenites, metadiorites, metafelsites, etc., under still greater heat, increased probably, as Mallet suggests, by mechanical energy in crushed strata being converted into heat, become completely fused, and are then outpoured upon the surface either by the elastic force of the steam generated, or by the pressure and squeezing produced by the folding of the crust of the earth, so common in mountainous regions. According to this view, every portion of the earth's crust has been worked over and over again, passing through the several conditions of soil, sediment, stratified rock, metamorphic rock, and igneous rock, perhaps many times in the course of the geological history of the earth, and we look in vain for the primitive rock of the earth's crust.

CHAPTER V.

STRUCTURE COMMON TO ALL ROCKS.

We have thus far given a brief description of the three classes of rocks, their structure and mode of occurrence. There are still, however, several important kinds of structure which are common to all these classes of rocks, and require description. These are *joints*, *fissures*, and *veins*. *Mountain-chains*, as involving all kinds of rocks and all kinds of structure, and as summing up in their discussion all the principles of structural and dynamical geology, must be taken up last.

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* American Journal of Science and Arts, vol. xi, p. 119, February, 1876.

SECTION 1.—JOINTS AND FISSURES.

Joints.

All rocks, whether stratified or igneous, are divided, by cracks or division-planes, in three directions, into separable irregularly prismatic blocks of various sizes and shapes. These cracks are called joints. In *stratified* rocks the planes between the bedding constitute one of these division-planes, while the other two are nearly at right angles to this and to each other, and are true joints. In *igneous* rocks all the division-planes are of the nature of joints. In *sandstone* these blocks are large and irregularly prismatic; in *slate*, small, confusedly rhomboidal; in *shale*, long, parallel, straight; in limestone, large, regular, cubic; in *basalt*, regular, jointed, columnar; in granite, large, irregularly cubic, or irregularly columnar. On this account a perpendicular rocky cliff usually presents the appearance of huge, irregular masonry, without cement.

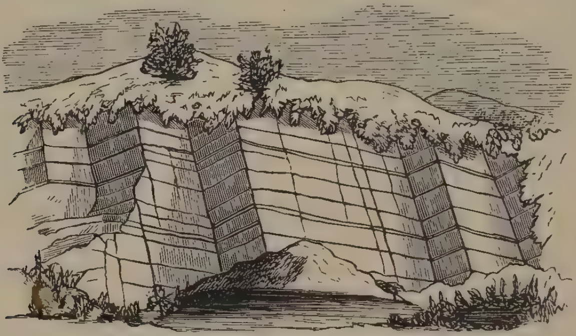

FIG. 197.—Regular Jointing of Limestone.

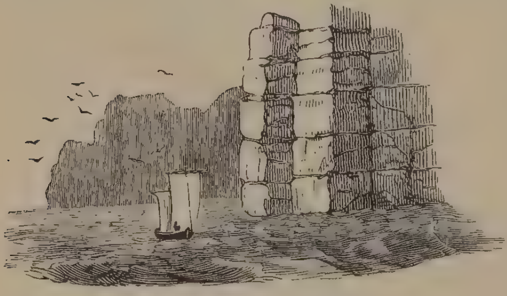

FIG. 198.—Granitic Columns.

The *cause* of joints is partly the shrinkage of the rock in the act of consolidation from sediments (lithification), as in stratified rocks, or in cooling from a previous condition of high temperature, as in the igneous and metamorphic rocks, and partly the crushings and torsions to which all rocks are subjected by movements of the crust. These last kinds graduate usually into the great fissures.

Fissures, or Fractures.

These must not be confounded with joints. Joints are cracks in the *individual strata* or *beds;* fissures are fractures in the *earth's crust*, passing through many strata, and even sometimes through many formations. The former are produced by shrinkage and perhaps other causes; the latter by movements of the earth's crust. Fissures, therefore, are often fifty or more miles in length, thirty to fifty feet in width, and pass downward to unknown but certainly very great depths. They often break through the crust into the sub-crust liquid.

Cause.—The cause of great fissures is evidently always movements, either by foldings or by liftings of the earth's crust. In either case there would be formed a parallel system of fissures in the direction of the folds, and therefore at right angles to the direction of the folding or lifting force. Fissures are usually thus found *in systems parallel among themselves*, and to the axes of mountain-chains. Through such fissures igneous rocks in a fused condition are often forced, forming dikes and overflowing sheets. Besides the principal fissures just explained, Hopkins has shown that, in the case of the formation of mountains, there would be formed also other smaller fissures at right angles to these.

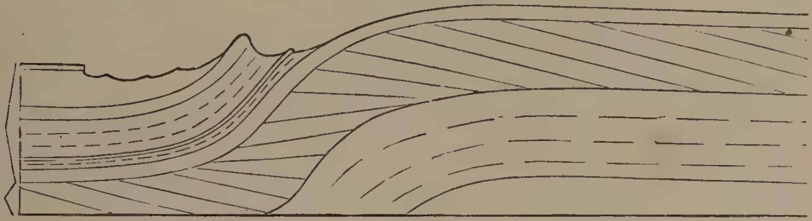

FIG. 199.—Section of Nutria-Fold, New Mexico (after Gilbert).

Nearly always the walls on the two sides of a fissure do not correspond with each other, but one side has been pushed up higher or dropped down lower than the other. Such a displacement is called a *fault*, a slip, or dislocation. This may occur in fissures in any kind of

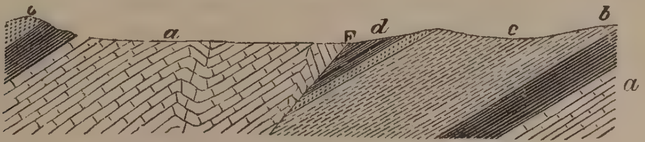

FIG. 200.—Fault in Southwest Virginia: *a*, silurian; *d*, carboniferous (after Lesley).

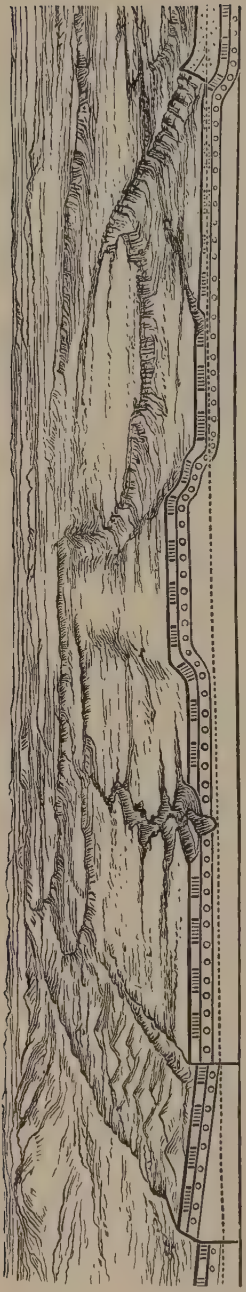

Fig. 201.—Faults and Monoclinal Folds of Plateau Region; section 90 miles long (after Powell).

rock, but is most marked and most easily distinguished in stratified rocks. When the strata are sufficiently flexible to admit it, they are bent instead of broken, and a monoclinal fold is formed instead of a fault (Fig. 199). When the fissure is filled at the moment of its formation with fused matter from beneath, it is called a *dike.* When it is not filled at the moment of its formation with igneous injection, but *slowly* afterward with *other matter*, and by a *different process*, it is called a *vein. Dikes* we have already discussed (p. 218); *veins* we will discuss later; we are concerned here only with *faults.*

Faults.—In faults the extent of vertical displacement varies from a few inches to hundreds or even thousands of feet. In the Appalachian chain there occur faults in which the vertical dislocation is 5,000 to 20,000 feet. In Southwest Virginia, according to Rogers, there is a line of fracture extending parallel to the Appalachian chain for eighty miles, in which there is a vertical slip of 8,000 feet,* the Lower Silurian being brought up on one side until it comes in conjunction with the Lower Carboniferous on the other (Fig. 200). In Western Pennsylvania, according to Leslie, there is another fault extending for twenty miles, in which the lowermost of the Lower Silurian is brought up on a level with the uppermost of the Upper Silurian, the whole Silurian strata being at this place 20,000 feet thick, so that one may stand astride of the fissure with one foot on the Trenton limestone (Lower Silurian), and the other on the Hamilton shales (Devonian).† On the north side of the Uintah Mountains there is a slip, according to Powell, of nearly 20,000 feet.‡ The Sevier Valley fault, Utah, may be traced partly as a slip, partly as a monoclinal fold, for 225 miles (Gilbert). On the west side of the Wahsatch range there is a fault of 40,000 feet (King),[*] and on the east side of the Sierra one of at least 15,000 feet.[†]

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* Dana's Manual, p. 399. † Manual of Coal, p. 147.

‡ Exploration of Colorado River, p. 156.

But nowhere on this continent, or perhaps in the world, are fissures and faults developed on so grand a scale as in the high Plateau region, i. e., the region bounded by the Wahsatch, the Uintah, and the Colorado Mountains. The whole of this elevated region is traversed by a system of north and south fissures, extending for hundreds of miles, by which the almost horizontal strata are broken into huge oblong prismatic blocks many miles wide. The slipping of these blocks, some to a higher and some to a lower level, with a difference of 1,000 to 5,000 feet, or even in some cases 12,000 feet, has given rise to the remarkable series of north and south cliffs, which, together with the equally remarkable east and west cliffs, due to erosion, to be described hereafter (p. 283), form so striking a feature of the scenery of this region. The accompanying section and perspective view (Fig. 201), taken from Powell, shows several of these occurring in a distance of 90 miles.[‡]

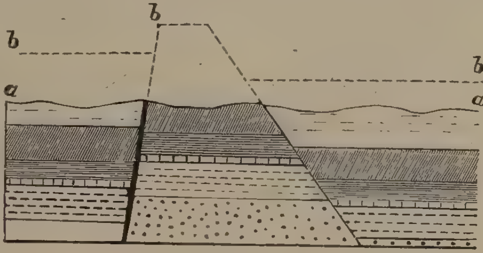

Fig. 202.

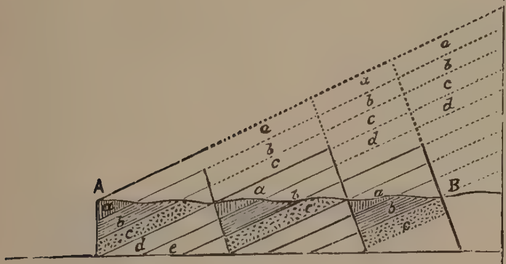

Fig. 203.—Strata repeated by Faults.

These fissures were formed by the elevation of the Plateau region, and are parallel to the axis of elevation; on each side of which they are arranged with wonderful regularity. They were formed in very recent geological times, probably late Pliocene and Quaternary,[#] and possibly reaching even into the present epoch, and are therefore little affected by erosion. Add to this the nakedness of the rocks and the horizontality of the strata, and it is easy to see what an admirable field is here afforded for the study of faults.

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[*] Survey of the Fortieth Parallel, vol. i, pp. 728–746.

[†] Le Conte, American Journal of Science, vol. xvi, p. 101, 1878.

[‡] The Kaibab fold and fault is 300 miles long with a slip of 7,000 feet. The Jordan-Araba fault, which gave origin to the Dead Sea, may be traced 350 miles (Nat., 44, p. 100, 1891).

[#] Dutton, Geology of the High Plateaus, p. 35.

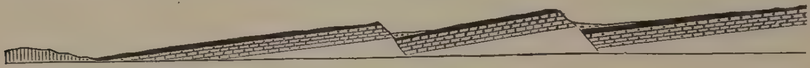

Fig. 204.—Section through Portion of Plateau Region of Utah, showing a Succession of Faults (after Howell).

If such slips were suddenly produced by violent convulsion, then, at the time of formation, there must have been a steep (Fig. 202) or sometimes even an overhanging escarpment (Fig. 200), equal to the displacement. In *some* cases there is such an escarpment or line of steep mountain-slope corresponding to the line of slip. In the Colorado Plateau region the north and south cliffs are produced by faults (Powell). The Zandia Mountains, New Mexico, are produced by a drop of 11,000 feet on the western side, leaving an escarpment still 7,000 feet high (Gilbert). The precipitous eastern slope of the Sierra and western slope of the Wahsatch are the result of faults. In the Basin Range region also many of the ridges are formed by faults. But in many cases there is no such escarpment, the two sides of the fault having been cut down to one level by subsequent erosion, so that the unpractised eye detects nothing unusual along the line of fracture and slip. In Fig. 202 the strong line *a a* shows the present surface, while the dotted line *b b b* shows the surface after the displacement as it would be if unaffected by erosion. In many cases, however, it seems more probable that there never existed any such escarpment as represented in Fig. 202, but that the displacement was produced by a *slow*, *creeping motion*, or else by a succession of smaller sudden slips probably accompanied with earthquakes (p. 116), and thus that the slipping and the denudation have gone on together *pari passu*. In Fig. 231, on page 266, the upper part shows the great Uintah fault restored, while the lower part shows the actual condition of things produced by erosion.

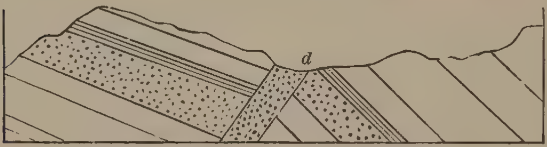

Fig. 205.—Fault with Change of Dip: *d*, dike.

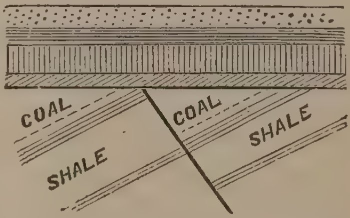

Fig. 206.—Unconformity on Faulted Strata.

When faults occur in inclined outcropping strata, the same series of strata may be repeated several times, as in Fig. 203. In such a case, the observer walking over the surface of the country from *A* to *B* might suppose here a series of nine strata, whereas there are but three strata, *a*, *b*, *c*, three times repeated. Fig. 204 is a natural section showing this. Sometimes the dip of the strata on the two sides of a fault are not parallel, the change of inclination being effected at the time of the displacement, as shown in Fig. 205. Upon the eroded surface of such dislocated strata, by subsequent subsidence, other strata may be unconformably deposited (Fig. 206).

Law of Slip.—In faults the plane of fracture is *sometimes vertical*, but much more generally it is more or less *inclined*. The inclination is called the *hade*. In such cases, in by far the larger number of great faults, the strata on the upper side (hanging wall) of the fracture have *dropped down*, while the strata on the lower side (foot-wall) have gone *up*, as in Figs. 207 and 208 and nearly all the previous figures. The fissure hàdes to the down throw. These are called *normal* faults. In some cases of strongly-folded strata, however, the hanging wall seems to have been pushed and made to slide upward over the foot-wall as if by powerful horizontal squeezing. This is the case with the great slip in Southwestern Virginia, represented in Fig. 200. These are called *reverse* faults. In several hundred cases of great fissures, examined by Phillips, in England, nearly all followed the law of normal faults.* Fig. 207 is a section across Yarrow Colliery, in which all the slips follow this law. Of the numerous slips figured by Powell, Gilbert, and Howell, as occurring in the Plateau and Basin Range region, nearly all follow this law. Fig. 208 is a section illustrating this fact.

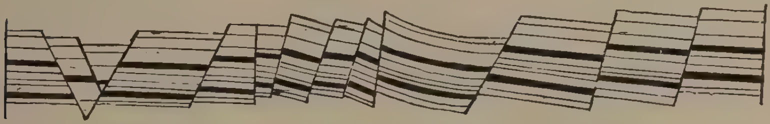

FIG. 207.—Section across Yarrow Colliery, showing the Law of Faults (after De la Beche).

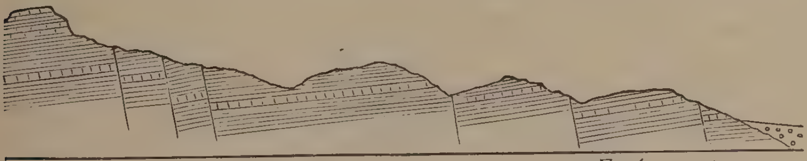

FIG. 208.—Section of Pahranagat Range, Nevada, showing the Law of Faults (after Gilbert).

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* Phillips's Geology, p. 35.

Explanation of the Direction of Slipping.—Reverse faults are nearly always found in strongly-folded strata such as characterize the structure of most mountain ranges, and are evidently formed by powerful lateral *pressure* in the act of mountain formation. The manner in which folds are pushed over until they become reverse faults is shown in the accompanying figures (Fig. 209, *A*, *B*, and *C*). In extreme cases the fault-plane becomes nearly horizontal, *C*. These are called *thrust-planes.**

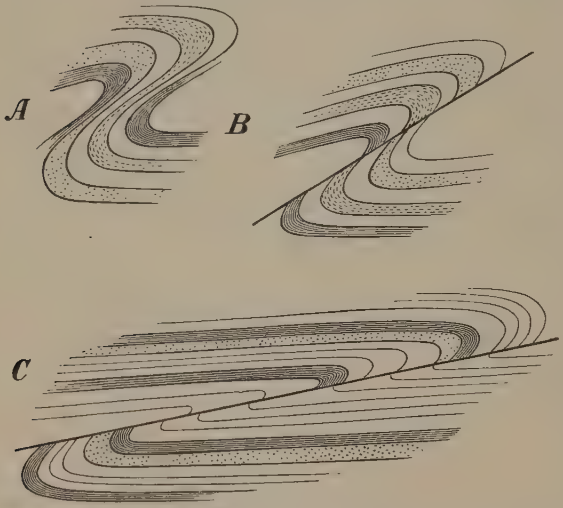

Fig. 209.—Diagrams showing how Reverse Faults are formed (after De Margerie and Heim).

The explanation of *normal* faults is not so obvious. In the case of great faults of this kind the explanation is probably as follows: Suppose a portion of crust lifted by intumescence of sub-crust layer, produced either by access of water from above or by hydrostatic pressure transferred from a subsiding area in some other perhaps distant place. The crust would be broken by more or less parallel fissures into great

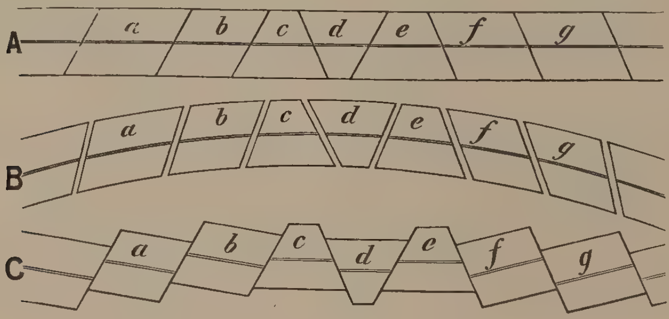

Fig. 210.—Diagrams showing how Normal Faults are probably formed.

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* Extreme examples of thrust-planes, such as those in the Scottish Highlands, seem to be formed in a rigid crust by fracture and overriding without folding.

oblong blocks many miles in extent. Since the fissures are usually more or less inclined, these crust-blocks would be either rhomboidal or wedge-shaped (Fig. 210, *A*). As the crust rose into an arch these blocks would separate (Fig. 210, *B*). As soon as the tension is relieved by escape of elastic vapors or lava or both, the blocks would readjust themselves by gravity into new positions. In doing so the rhomboidal blocks *a b f g* would tilt over on the overhanging side and heave up on the obtuse-angle side, producing in every case *normal* faults, and the wedge-shaped blocks *c d e* would sink bodily lower or float bodily higher according as the base of the wedge was upward or downward, producing again in every case normal faults, as shown in Fig. 210, *C*. The result of such readjustment of crust-blocks is admirably shown on a large scale in the structure of the Basin region, and especially in Southeastern Oregon (Fig. 211). The fracturing and tilting here have been so recent (beginning of Quaternary) that erosion has had little effect in modifying the orographic forms. It is seen that the upheaved side of every crust-block forms a mountain-ridge, while the dropped side forms a valley on which drainage waters accumulate to form a lake.

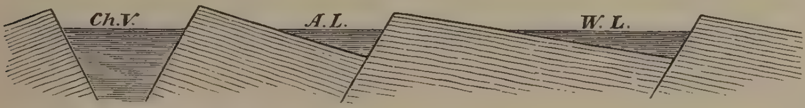

FIG. 211.—Sketch section through Warner and Abert Lakes, S. E. Oregon (after Russell): *W. L.*, Warner Lake; *A. L.*, Abert Lake; *Ch. V.*, Chemaukan Valley.

Thus where fissures are formed by lateral *pressure* or crushing, *reverse* faults are formed; but where they are formed by lateral tension or stretching, *normal* faults are formed.*

SECTION 2.—MINERAL VEINS.

All rocks, but especially metamorphic rocks in mountain-regions, are seamed and scarred in every direction, as if broken and again mended, as if wounded and again healed. All such seams and scars, of whatever nature and by whatever process formed, are often called by the general name of *veins*. It is better, however, that dikes and so-called granite-veins, or all cases of fissures filled at the moment of formation by igneous injection, should be separated from the category of veins. True veins, then, are accumulations, mostly in fissures, of certain mineral matters usually in a purer and more sparry form than they exist in the rocks. The accumulation has in all cases taken place subsequently to the formation of the fissures, and by a slow process.

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* Reade has shown (Origin of Mountains, chap. viii) that crust-blocks formed by tension and resting on *any kind of yielding foundation*, whether solid or liquid, would settle so as to form normal faults. It is probable, therefore, that smaller faults of this kind may be formed without a sub-crust liquid.

Kinds.—Thus limited, veins are of three kinds: *Veins of segregations*, *veins of infiltration*, and great *fissure-veins.* These three, however, graduate into each other in such wise that it is often difficult to determine to which we must refer any particular case. Some writers make many other kinds, but these may be regarded as intermediate varieties.

1. *Veins of Segregation.*—In these the vein-matter does not differ greatly from the inclosing rock. Such are the irregular lines of granite in granite, the lines differing from the inclosing rock only in color or texture; also irregular veins of feldspar in granite or in gneiss. Under the same head belong also the irregular streaks, clouds, and blotches, so common in marble. In these cases there seems to be no distinct line of separation between the vein and the inclosing rock —*no distinct wall to the vein.* The reason is, these veins are not formed by the filling of a previously-existing fissure, but by the segregation of certain materials, in certain spots and along certain lines, from the general mass of the rock, either when the latter was in plastic condition from heat and water, or else by means of percolating water, somewhat as *concretions* of lime, clay, iron-ore, and flint, are formed in the strata (p. 196).

2. *Veins of Infiltration.*—Metamorphic rocks have, probably in all cases, been subjected to powerful horizontal pressure. Besides the wide folds into which such rocks are thus thrown and the great fissures thus produced, the strata are often broken into small pieces by means of the squeezing and crushing. The small fissures thus produced are often filled by *lateral secretion* from the walls, or else by slowly-percolating waters holding in solution the more soluble matters contained in the rocks. The process is similar to the filling of cavities left by imbedded organisms (p. 201), and still more to the filling of vapor-blebs in traps and lavas, and the formation of agates and carnelian amygdules (p. 224). In veins of this kind, therefore, a beautiful *ribbon-structure* is often produced by the successive deposition of different-colored materials on the walls of the fissure. Veins of this kind also, since they are the filling of a previously-existing fissure, have *distinct walls.* The filling consists most commonly of silica or of carbonate of lime. Gash-veins of authors are probably larger veins of this kind.

3. *Fissure-Veins.*—These are fillings of the great fissures produced by movements of the earth's crust. When these fissures are filled at the time of formation by igneous injection, they are called *dikes;* but if subsequently with mineral matter, by a different process, to be discussed hereafter, they are *fissure-veins.* These veins, therefore, like

dikes, outcrop over the surface of the country often for many miles, fifty or more. Like dikes, also, they are often many yards in width, and extend to unknown, but certainly very great, depths. Like dikes and fissures, also, they occur in parallel systems and are often faulted.

Characteristics.—The most obvious characteristics of the veins of this class are their *size*, their *continuity* for great distances and to great depths, their faulted condition, and their occurrence in *parallel systems*. As the vein is a filling of a previously-existing fissure, the distinction between the vein and the wall-rock is usually quite marked. In many cases, in fact, the vein-filling is separated from the wall-rock by a layer of tenacious, clayey matter called a *selvage* or *gouge*. The selvage is probably formed by decomposition of the wall-rock in immediate contact with the vein, by circulating water assisted doubtless by crushing of the rocks by repeated movements of the walls. These movements also often produce a striation and polishing of the walls called "*slicken-sides*." The *contents* of fissure-veins are also far *more varied* than those of other classes.

Metalliferous Veins.—Some metals, particularly *iron*, occur principally in great beds, being accumulated by a process already described (p. 150). Others, especially *lead*, often accumulate in flat cavities between the strata, especially of limestone. But most metals occur in veins. All the kinds of veins mentioned above may contain metals, but the *segregative* veins are usually too irregular and uncertain, and the *infiltrative* veins too small, to be profitable. True, profitable metalliferous veins are almost always great *fissure-veins*. We will speak, therefore, principally of these, and the further description of fissure-veins is best undertaken under this head.

Contents.—The contents of metalliferous veins are of two general kinds, viz., *vein-stuffs* and *ores*. The principal vein-stuffs are quartz, carbonate of lime (calc-spar), carbonate of baryta, carbonate of iron, sulphate of baryta (heavy spar), and fluoride of calcium (fluor-spar). By far the most common of these is *quartz*, and next is *calc-spar*. Often, however, the vein-stuff is an aggregate of minerals forming a true rock. Nearly the whole of a vein consists usually of vein-stuff. The *ore* exists in comparatively small quantities, sometimes forming a central *rib* or *sheet*, as if deposited last (Fig. 212, *a b*); sometimes in irregular isolated masses called *bunches* or *pockets*, or in small strings, or grains, irregularly scattered through the vein-stuff and extending often a little way into the wall-rock.

The *chemical forms* in which metals occur are very various; sometimes they occur as pure metal (as always in the case of gold and platinum, and sometimes in the case of silver and copper), but more commonly in the form of metallic sulphides, metallic oxides, and metallic carbonates. Of these the metallic *sulphides* are by far the most common. It is worthy of remark that all these forms are comparatively very insoluble. The same is true of the vein-stuffs.

Ribboned Structure.—The ribboned or banded structure, already spoken of under Veins of Infiltration, is very commonly found in great fissure-veins. This structure is as characteristic of veins as the columnar structure is of dikes. The layers on the two sides usually correspond to each other (Fig. 212); sometimes the successive layers are of different color, giving rise to a beautiful, striped appearance. Sometimes the successive layers on both sides are of different materials, as in Fig. 213, in which the central rib, *d*, is galena, and *a a*, *b b*, *c c*, are successive layers of quartz, fluor, and baryta. Sometimes, in cases of quartz-filling, the layers are agate, except the center, which is filled up with a comb of interlocking crystals, as in Fig. 214. The same occurs often in amygdules, the last filling being crystalline. Sometimes there is evidence of successive openings and fillings, as in Fig. 215, where *a* represents quartz-crystals, interlocking in the center and based on agate layers, *b b*, while *c* represents quartz with disseminated copper pyrites. In this case it seems probable that 1 and 2 were the walls when the agate and quartz-filling took place, and that afterward the fissure was reopened along 2, so that the walls became 2 and 3, and the new fissure thus formed was filled with cupriferous quartz. The same is well shown in Fig. 216, where *a*, *b*, *c*, *d*, *e*, *f*, are successive quartz-combs, separated by 2, 3, 4, 5, 6, which are clay selvages, and therefore old walls.

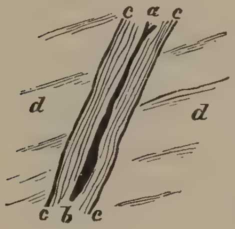

FIG. 212.

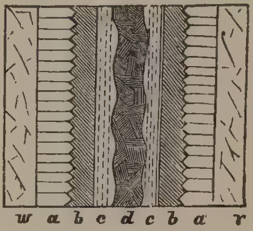

FIG. 213.

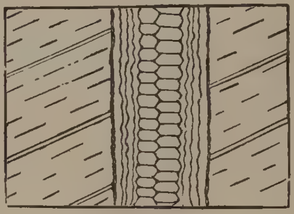

FIG. 214.

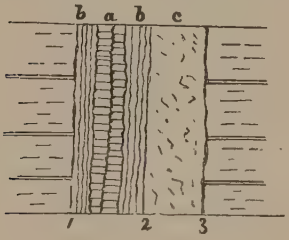

FIG. 215.

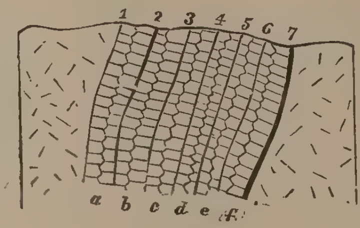

FIG. 216.

Irregularities.—Although more regular than other kinds, yet fissure-veins are also often quite irregular—sometimes branching, sometimes narrowing or pinching out in some parts and widening in others (Fig. 217), sometimes dividing and again coming together, and thus inclosing a portion of the wall-rock (Fig. 218). Such an inclosed mass of country rock in the midst of a vein is called a "*horse.*" Many of these irregularities are probably the result of movements after the fissure was formed, or even after it was filled. Thus, if *a b c d* (Fig. 217) be one wall of an irregular vein, then it is probable that *a′ b′ c′ d′* was the original position of this wall; but, *before* it was filled, it slipped up to its present position. Or, an open fissure may pinch together in places by what is called *creeping* of the strata of the wall, i. e., a mashing and filling in by pressure of superincumbent weight. Again, movements may reopen a fissure *after* it is filled. In such cases, if the adhesion of the filling to the wall is strong, portions of the wall-rock are torn away; and, if a second filling takes place, a "horse" is formed. Thus *a a a* and *b b b* (Fig. 218) represent the two original walls of an irregular vein; but subsequent movement reopened the fissure to *b′ b′ b′* and tore away the horse *H*, after which the vein was again filled. Also crust-movements may form not only a single clean fissure, but sometimes many small, irregular fractures, with wall-rock between. The filling of these form irregular veins in which vein-stuff is often inextricably mingled with country rock. The vein may thus be filled with a *troop of horses.* Sometimes there is no distinct fissure but only a loosening of the rock along a certain plane, and the *incipient* fissure thus formed is filled with vein-matter. Sometimes repeated movements break up the rock into a rubble-filled fissure, which by filling form a *brecciated vein.* Finally, in some rocks, especially limestone, percolating waters will hollow out passages in the most irregular way. These also may become filled with vein-stuff and give rise to irregular veins.

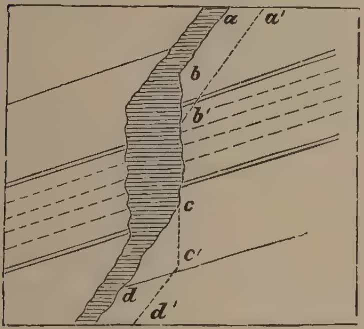

Fig. 217.—Irregularities in Veins.

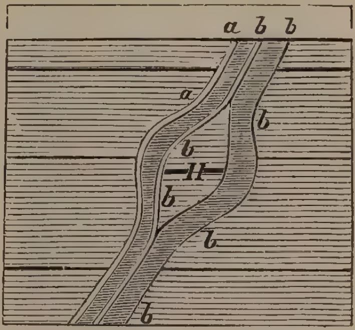

Fig. 218.—Irregularities in Veins.

Veins, of course, *usually intersect* the strata; but in some cases where strata-plains are highly inclined the opening is between these planes, and the veins are, therefore, conformable with them.

Age.—The *relative* age of veins in the same region is determined in the same way as that of dikes, viz., by the manner in which they intersect each other; the intersecting vein being, of course, younger than the intersected vein. Thus in Fig. 219, which is a section of a hill-side in Cornwall, it is evident that the tin vein, *a*, is the oldest, since it is intersected and slipped by all the others. The copper vein, *b*, is older than the clay-filled fissure, *c*. There is a fourth fissure, *d*, newer than *a*, but its relation to *b* and *c* is not shown in this section.

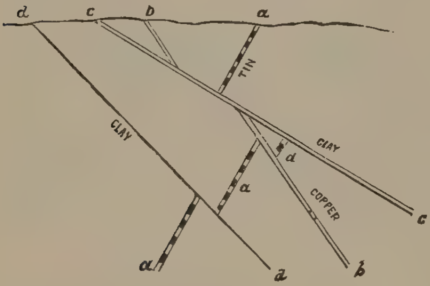

FIG. 219.

The *absolute* age of fissure-veins, or the geological period in which the fissure was formed, can only be determined by the stratified rocks through which it breaks. The lead-veins of Cornwall (*b b*, Fig. 221) break through the Cretaceous. Their fissures were probably formed by the changes or oscillations which closed the Cretaceous and inaugurated the Tertiary period. The auriferous veins of California break through the Jurassic; and, as there are good reasons for believing that the Sierras were formed at the end of the Jurassic, it is probable that these fissures were formed at that time by the foldings of the strata consequent upon the pushing up of this range. The *filling*, of course, was a slow, subsequent operation, but commenced then.

Surface-Changes.—Mineral veins seldom or never outcrop on the surface in the condition we have described them. On the contrary, there are certain changes which they undergo through the influence of atmospheric agencies, which render their appearance along their outcrop quite different from that of the same vein at some depth below. A knowledge of these changes is, of course, of the greatest practical importance. They are, however, extremely various, differing not only according to the metallic contents, but also according to the nature of the vein-stuffs, and therefore must be learned by observation in each country. We will give three of the most constant as illustrations.

Cupriferous Veins.—The original form in which copper seems to exist in veins is *copper pyrites*, a double sulphide of copper and iron ($CuFeS_2$). Now, along the *back* or outcrop of copper-veins, to a depth of thirty to sixty feet, the vein usually contains no copper at all, but consists of vein-stuff (more or less changed, according to its nature), among which are scattered masses of a dark reddish or brownish hydrated peroxide of iron, in a *light, spongy condition.* This peculiar form of peroxide of iron, so characteristic of the crop of copper-veins, is called by the Cornish miners *gossan*, and by the German and French miners *iron hat* (*eiserner hut; chapeau de fer*).* Below the influence of atmospheric agencies the vein is in its original condition, i. e., consists of vein-stone containing disseminated masses of copper pyrites. Just at the junction of the changed with the unchanged vein—i. e., running along the back of the vein at a depth varying from thirty to sixty feet—occur rich accumulations of copper, as native copper, red and black oxides of copper, green and blue carbonates of copper, etc. These facts are illustrated by Fig. 220, which is a section of the Ducktown mines of Tennessee. The irregular line, *s s*, is the outline of a hill, along the crest of which the vein outcrops; the part *b* consists almost wholly of gossan, with only small masses of quartz-vein stuff; *a* is the rich accumulation of copper ore, here about two or three feet thick; and *c* is the unchanged vein, consisting of vein-stuff, inclosing arsenical pyrites, and copper pyrites in very large quantities.

These phenomena may be explained as follows: There can be no doubt that the gossan represents copper pyrites, from which the copper has been entirely washed out, leaving the iron in an oxidized condition. Thus the whole of the copper from *b* (and probably from much more than *b*, for the process of denudation has gone on *pari passu* with the process of leaching) has been leached out and accumulated at *a*. Further, it is probable that the process was as follows: When copper pyrites is exposed to moist air it slowly oxidizes into sulphates of iron and copper ($CuFeS_2 + 8O = FeSO_4 + CuSO_4$). The *iron* sulphate (probably assisted by reaction with alkaline or earthy carbonates) quickly passes into ferric oxide and is left in a spongy condition, while the copper sulphate is carried downward. This much seems certain, but, by what subsequent process the copper takes all the forms actually found at *a*, is little understood, although it is probable that the car-

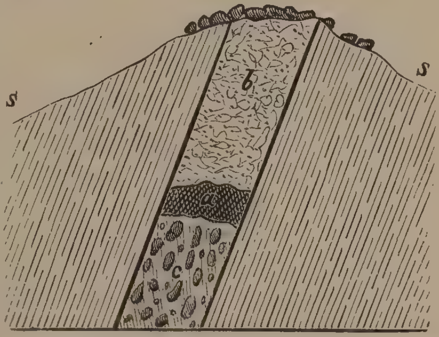

FIG. 220.—Ducktown (Tennessee) Copper Vein, showing Surface-Changes (after Safford).

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* These terms are applied to many alteration-products containing iron, but they are especially conspicuous in copper veins.

bonate is produced by the reaction, on the sulphate, of waters containing alkaline carbonate or bicarbonate of lime.*

Plumbiferous Veins.—The natural or original form in which lead occurs in veins is *sulphide* of lead, or *galena.* But along the backs or outcrops of lead-veins it is found more commonly as carbonate. The explanation seems to be as follows: Lead occurs mostly in veins intersecting, or in sheets between, strata of limestones. It is probable that the galena (PbS) is oxidized by meteoric agencies and becomes sulphate ($PbSO_4$), and then the sulphate, by reaction with the carbonate of lime derived from the wall-rock or from the calc-spar of the vein-stuff, becomes carbonate, thus: $PbSO_4+CaCO_3=PbCO_3+CaSO_4$. In proof of this process it is stated † that galena, thrown out of the old mines of Derbyshire among rubbish of limestone, has all, in the course of ages, been changed into carbonate. Moreover, it is not uncommon to find in lead veins masses of sulphide changed *on the outside* into carbonate.

Auriferous Quartz-Veins.—Gold is found either in quartz-veins, intersecting metamorphic slates (quartz-mines) or in gravel-drifts in the vicinity of these (placer-mines). Originally it existed in the quartz-veins usually associated with metallic sulphides, particularly the *sulphide of iron* (pyrites). If the pyrites be dissolved in nitric acid, the gold is left as minute threads and crystals. Evidently, therefore, it exists in minute threads and crystals scattered through the pyrites. Now, when such a vein is exposed to meteoric agencies, the pyrites is oxidized, partly as soluble sulphate, and carried away, and partly as insoluble reddish peroxide, which remains.‡ The quartz-vein stone is, therefore, left in a honey-comb condition by the removal of the pyrites, and more commonly stained of a rusty color by the peroxide. Among the cells of this rusty cellular quartz the gold is found in minute, sharp grains, evidently left by the removal of the pyrites. Hence, in an auriferous quartz-vein, along the outcrop to a depth of thirty to sixty feet (i. e., as far as meteoric agencies extend) gold is found *free* in small grains among the cellular quartz; but below the reach of these agencies it is inclosed in the undecomposed pyrites.

Placer Mines.—If a mountain-slope, along which outcrop auriferous quartz-veins, be subjected to powerful erosion by water-currents, then in the stream-beds will be found gravel-drifts, composed partly of the country rock and partly of the quartz vein-stone. Among the gravel will be found particles of gold, washed out from the upper parts of the veins. By the sorting power of water the heavy gold particles are apt to accumulate mostly near the bed of the gravel-deposit (bed-rock). These gravel-deposits are the *placers*. In these, the gold-particles, like the stone-fragments, are always *rounded* and *worn* by attrition.

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* Bischof, Chemical and Physical Geography, vol. iii, p. 509.

† De la Beche, Geological Observer, p. 794.

‡ Probably the iron sulphide is oxidized to the condition of sulphate, then reduced to carbonate by water containing alkaline carbonate or bicarbonate of lime, and lastly peroxidized by exchanging carbonic acid for oxygen (Bischof).

Some Important Laws affecting the Occurrence and the Richness of Metalliferous Veins.

1. *Metalliferous veins occur mostly in disturbed* and *highly-metamorphic* regions, where the strata are tilted, and folded, and metamorphosed. The tilting and folding are necessary to the formation of *fissures;* and the conditions under which metamorphism takes place seem necessary for the subsequent *filling* with mineral matter. Mineral veins, therefore, occur mostly in *mountain regions*, and in the vicinity of more or less obvious evidences of *igneous agency*. Lead-veins seem to be an exception to this rule. They are often found in undisturbed regions where the rocks are entirely unchanged. The rich lead-mines of Illinois, Iowa, and Missouri, are notable examples, the country rock being horizontal, fossiliferous limestones of the Palæozoic era.

2. *Metalliferous veins occur mostly in the older rocks.* In Great Britain, for example, no profitable veins occur above the *Trias*. This rule, which was regarded as of great importance by the older geologists, is not so regarded now. There seems to be no close connection between the occurrence of metalliferous veins and simple age alone; the connection is rather with metamorphism. Metamorphism, as we have seen (p. 228), is most common in the older rocks, and becomes more and more exceptional as we pass upward. The occurrence of metalliferous veins follows the same law. But when the newer rocks *are* metamorphic, they are as likely to contain veins as are rocks of the older series. The metalliferous veins of California occur in Jurassic, Cretaceous, and even Tertiary strata; but these strata are there highly metamorphic, and strongly folded. In Bohemia, also, and elsewhere, metalliferous veins occur in the higher series (Phillips's Geology, p. 549).

3. *Parallel* veins are apt to have *similar* metallic contents, while veins running in different directions (unless sometimes at right angles) are apt to contain different metallic contents. Thus, the nearly east-and-west lodes of Cornwall, *a a a* and *c c* (Fig. 221), contain tin and copper, while the north-and-south courses, *b b*, contain lead and iron. The auriferous veins of California are parallel to each other and to the Sierras, except a few smaller ones, which are at right angles to these. The reason of this rule is, that parallel fissures belong to the same system, and were therefore formed at the same time, broke through the same strata, and were filled under similar conditions, and therefore with the same material; while fissures running in different directions

(unless in some cases at right angles, p. 237) were probably formed at different times, broke through different strata, and were filled under different conditions. Thus, the east-and-west veins of Cornwall, *a a*, are pretriassic; the north-east and south-west veins, *c c*, break through the Trias, and are therefore post-triassic,* while the north-and-south veins break through the Cretaceous. The auriferous veins of California all break through the Jurassic; they, or their fissures, were probably produced at the same time, viz., at the time of pushing up of the Sierras.

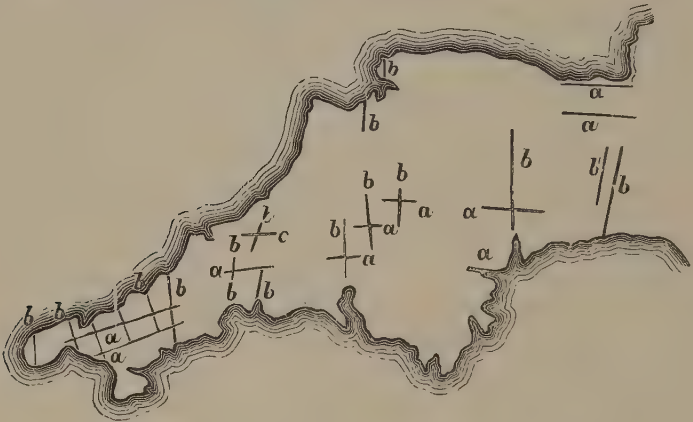

FIG. 221.—Map of Cornwall: *a* and *c*, tin and copper; *b*, lead and iron.

4. A change of country rock of an outcropping vein is apt to determine some change, either in the contents or in the richness of the vein. Nevertheless, there is not that close connection between the nature of the country rock and the vein-contents which obtains in infiltrative veins. The reason is, that infiltrative veins derive their contents entirely from the wall-rock on either side, while fissure-veins derive their contents from *all* the strata through which they break, even to great depths, and especially from the deeper strata. The nature of the surface or country rock is, therefore, only *one* factor, determining the vein-contents.

5. Metallic veins are usually richer near their point of intersection with granite or with an igneous dike, especially if the strata have suffered metamorphism. This shows the influence of such heat as is present in metamorphism, in determining the metallic contents.

6. If two veins cross each other, especially if at small angle, one or both are apt to be richer at the point of crossing. No sufficient reason has been given for this law. It is probably due to the reaction of waters bearing different materials circulating in the two fissures.

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* De la Beche, Geological Observer, p. 757.

7. Since veins are the fillings of fissures, they are often slipped by each other or by dikes or by simple unfilled fissures. If a metalliferous vein is thus slipped, according to the law of slips already given (p. 241) the foot-wall of the vein has usually gone upward, and the hanging wall dropped downward. The great importance of this law in practical mining is sufficiently obvious. All the slips of Fig. 219, except that made by the fissure *c*, follow this law.

8. *The surface-indications* are to be learned by attentive observation in each case. We have already given these in the case of copper, lead, and gold.

Theory of the Origin of Metalliferous Veins.

Our knowledge of the conditions under which, and the chemical process by which, fissures have been filled with mineral matter, is yet, unfortunately, very imperfect. Many vague and crude theories have been proposed. Some have supposed that they have been filled in the manner of dikes and granite veins, by igneous injection; others, that these fissures, opening below into the regions of incandescent heat, have been filled by *sublimation*, i. e., by vaporization of certain materials and their condensation in the fissures above. Some suppose that electric currents, such as are known by observation to traverse certain veins, have been the chief agents in the transference and accumulation of the mineral matter. These three theories may be dismissed as being untenable or else as too hypothetical. Still others have thought that great fissures have filled in the same manner as the smaller fissures, and cavities of every kind found in the rocks, viz., by infiltration of soluble matters from the fissured rocks. There is certainly considerable analogy between small infiltrative veins and great fissure-veins in their mode of formation; yet there is a decided difference. The fillings of infiltrative veins are derived, in each part, entirely from the bounding rock on either side. The fissure is filled by a *lateral secretion* from its walls; the broken rocks heal themselves "by first intention" by means of a plasma oozing from the sides. But great fissure-veins derive their contents in each part from *all* the strata to great depths, and especially from the deeper strata. Hence the contents of these veins are far more varied.

Outline of the Most Probable Theory.—The contents of mineral veins seem to have been deposited from *hot alkaline solutions* coming up through fissures; in other words, from *hot alkaline springs*. We will attempt to show this first for the *vein-stuffs*, especially quartz, and then for the *metallic ores*, especially the metallic sulphides.

Vein-Stuffs.—1. *They were deposited from solutions.* (*a*) The *ribbon-structure* and the interlocked crystals (Figs. 212–216) suggest at once successive deposition from solution, especially as a similar structure occurs in the fillings of cavities of all kinds, which could not have been filled in any other way. (*b*) Quartz is by far the most common of all vein-stuffs. Now, as already explained (p. 233), there are two varieties of silica—one having a specific gravity of 2·2, the other 2·6. The dry way produces only silica-glass, which has a specific gravity of 2·2, while the variety of specific gravity 2·6, or true quartz, can not be formed except by the humid way.* In fact, this variety, as far as we know, is always produced by *slow* deposition from solution. Now, the quartz of veins is always the variety 2·6, and therefore was produced by slow deposit from solution. The beautiful crystals so often found in veins could be produced in no other way. (*c*) We have already seen (p. 233) that *fluid cavities* are a proof of formation by humid process. Now, such fluid cavities are especially abundant in vein-stuffs generally. They are best seen in quartz-vein stuffs, because of their transparency. (*d*) Not only quartz but many other minerals found among vein-stuffs are of such nature that it is difficult or impossible to understand how they could have been formed except by the humid way, as they will not stand fusing temperature.

2. *The solutions were hot.* (*a*) Fissures running deep into the interior of the earth could hardly remain empty of water. But from their great depth the contained waters must be *hot*. The solvent power of water, when heated to high temperature under pressure, is well known. Scarcely any substance wholly resists it. (*b*) The *fluid cavities* found in quartz and other vein-stuffs are not usually entirely filled, but contain a small *vacuous space*. Such a vacuous space indicates (p. 234) that the inclosed liquid was at high temperature at the time of being inclosed, and has since contracted on cooling. By heating the mineral until the cavity fills and the vacuous space disappears, we ascertain the temperature of deposit. Now, by this process the temperature of deposit of vein-minerals has been ascertained to vary from ordinary temperatures even up 300° and 350°.† (*c*) The invariable association of metalliferous veins with metamorphism demonstrates the agency of heat.

3. *The solutions were alkaline.* Alkaline carbonates and alkaline sulphides are the only natural solvents of quartz, the commonest of vein-stuffs. Moreover, when these waters contain excess of carbonic acid, as is almost always the case, they dissolve also the carbonates of lime, baryta, iron, etc., the next most common forms of vein-stuffs. In California and Nevada such hot alkaline carbonate and alkaline sulphide springs abound, and are daily depositing silica (quartz)

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* Recently under peculiar conditions crystallized quartz of specific gravity 2·6 has been formed by dry fusion.—American Journal of Science, vol. xvi, p. 155, 1878.

† Sorby, Quarterly Journal of the Geological Society, vol. xiv, p. 453 *et seq.*

and carbonates of lime and of iron, and even in some cases filling fissures.

Metallic Ores.—There seems no reason to doubt, then, that, in most cases at least, vein-stuffs have been deposited from hot alkaline solutions. Now, it is evident, from their intimate association with the vein-stuffs, that the *metallic ores* must have been deposited from the same solution. The exact nature of the solvent and the chemical reaction is still very doubtful. We may imagine many, by either of which the deposit might take place: 1. *Metallic sulphides* are by far the most common form of *ore*, and even when other forms exist we may in many cases trace them to sulphide as their original form (p. 248 *et seq.*). But metallic sulphides are slightly soluble in alkaline sulphides, and these latter are often found associated with alkaline carbonates in hot springs (solfataras), as in California and elsewhere. Such waters would hold in solution silica, carbonates of lime, etc., and metallic sulphides, and, coming up through fissures, would deposit them both *by cooling* and by *relief of pressure.* Or, 2. Alkaline carbonate waters holding in solution silica and lime carbonate for vein-stone, and also containing alkaline sulphide, *meeting* and mingling in the same fissure with *other* waters containing metallic sulphates, by reaction would precipitate metallic sulphides $(NaS+MaSO_4=NaSO_4+MS)$. This seems to be the reaction by which the inky waters of some of the hot springs of the California geysers are formed. Or, 3. The alkaline carbonates still remaining for vein-stone, metallic *sulphates*, in solution in the same waters *with organic matter*, would be reduced to the form of metallic sulphide, which, being insoluble, would be deposited.[*] Or, 4. Alkaline sulphide waters holding metallic sulphides and organic matters in solution—the acids of organic decomposition (humus acids) would neutralize the alkalinity and deposit the metallic sulphide. For greater clearness we annex a table expressing these processes:

$$\text{Alk.CO}_3+\text{HCO}_3+\begin{cases}\text{1. Alk.S}+\text{MS in sol}^{\text{n}}\text{ deposit } \mathit{MS} \text{ by } \textit{cooling.}\\ \text{2. Alk.S}+\text{MSO}_4\text{ meeting `` } \mathit{MS} \text{ `` } \textit{reaction.}\\ \text{3. MSO}_4+\text{org}^{\text{c}}\text{ mat}^{\text{r}} \text{ `` } \mathit{MS}\text{ `` } \textit{reduction.}\dagger\\ \text{4. Alk.S}+\text{MS}+\text{org}^{\text{c}}\text{ mat}^{\text{r}}\text{ insol}^{\text{n}}\text{ deposit }\mathit{MS}\text{ by }\textit{neutralization.}\end{cases}$$

There are many difficulties in the way of every attempt to place these reactions in a clear and distinct form, but in spite of these difficulties there seems little reason to doubt that great fissures have been filled by deposit from hot alkaline waters holding various mineral subtances in solution. The more *insoluble* substances are deposited in the vein, while the more *soluble* reach the surface as mineral springs.

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[*] It might at first seem that there is a chemical difficulty in this case—that metallic sulphate can not coexist in solution with alkaline carbonate, but would be precipitated as metallic carbonate. But it is evident that this reaction would not take place in a weak metallic solution, in the presence of *excess of carbonic acid*, since in this case the metallic carbonate is *soluble.*

[†] Francis C. Phillips has shown that powdered AgS reduced by H at high temperature takes the form of interlaced threads. Now, it is a curious fact that both gold and silver are often found in the form of threads.

This view is powerfully supported by the phenomena of hot alkaline springs in California and Nevada. The Steamboat Springs, near Virginia City, Nevada (so called from the periodic eruption of hot water and steam), come up through fissures in comparatively recent volcanic rock. The waters are strongly alkaline, and deposit silica in abundance. By this deposit the fissures are gradually filling up and forming veins. Some fissures are now partially and some entirely filled. The ribbon-structure in some cases is perfect. Moreover, sulphides of several of the metals, viz., iron, lead, mercury, copper, and zinc, have been found in the quartz-vein stuff. Here, then, we have true metalliferous veins forming under our very eyes.* So also at Sulphur Bank, Lake County, California, hot alkaline sulphide waters,† coming up from beneath, deposit both silica and cinnabar in small, irregular fissures and cavities, forming quartz-veins containing cinnabar. The deposit is so recent that the silica is sometimes still in a soft, hydrated condition, which cuts like cheese.‡

After this general discussion of the theory of metalliferous veins, we are now in position to state more clearly their mode of formation. Meteoric waters, circulating in the interior of the earth in any direction—downward, upward, or laterally—deposit slightly soluble matters in their course, in cracks, cavities, or great fissures, forming fossil casts, geodes, amygdules, infiltration-veins, and fissure-veins. As to *direction*, the *up-coming* waters, especially in metamorphic and volcanic regions, deposit most freely, and are most metalliferous, because they are hot and often alkaline, and therefore most powerful solvents, and, of course, cool gradually on approaching the surface. But that downward percolating waters may also deposit metallic ores is proved by the fact that these are sometimes found depending, like stalactites, from the roofs of cavities.# As to the different *kinds* of veins, those of *great fissures* are most prolific, because these fissures are the highways of water from the heated depths. But every kind of water-way will receive deposits; and, as the kinds of these are infinitely various and pass by insensible gradations into each other, so also will be the veins which fill them. The *open* fissure is the easiest and therefore the most traveled high-

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* Arthur Phillips, American Journal of Science, vol. xlvii, p. 194; and Philosophical Magazine, 1872, vol. xlii, p. 401.

† The water in this mine is 176° Fahr.—*Becker.*

‡ Le Conte, American Journal of Science, vol. xxiv, p. 23, 1882.

Schmidt, American Journal of Science, vol. xxi, p. 502, 1881. Chamberlain's Geology of Wisconsin, vol. iii, p. 495.

way. In these, therefore, we have the most typical veins, with their banded structure and their selvages, their great size and continuity. But in many cases crust-movements produce only *incipient* fissures, i. e., a loosening of the rock-cohesion, along planes affected with a multitude of small cracks, with country rock between. These loosened planes become also water-ways, and, by deposit, form those *irregular veins* so common everywhere, but especially in the cinnabar-veins of California. Or, again, crust-movements may produce not *clean open* fissures, but rather planes of shattered rock or rubble-filled fissures. Deposit in such a water-way forms a breccia of country rock, cemented with vein-stuff or *brecciated* veins. Or, again, in certain country rocks soluble in water, especially limestones, the rock is dissolved along the water-way, and the vein-stuff deposited *pari passu*, giving rise to what are called *substitution-veins.* In short, once conceive clearly that mineral veins are filled water-ways, and all these complex phenomena solve themselves. Even porous rocks like sandstones, because of their porosity, become the depositaries of vein-stuff, though not in paying quantities, except along lines or planes where water-transit is more easy and abundant. Examples of such deposits are found in the silver-bearing and copper-bearing sandstones of Utah and New Mexico.*

Thus there seems no longer any room for doubt that metalliferous veins are deposits from solutions in water-ways of any kind, but mostly from hot alkaline solutions coming up through great fissures. It is only the exact chemical reaction which is yet obscure. The work of the geologist is all but complete; the problem must now be turned over to the chemist. It may be interesting, however, before leaving this subject, to consider separately the auriferous veins of California, and apply to them the principles set forth above.

Auriferous Veins of California.—Gold is one of the most insoluble of substances, and the occurrence of this metal in veins has always been regarded as a difficulty in the way of the *solution theory.* The only free solvent of gold is a solution of *free* chlorine; but this does not exist in Nature. Nevertheless, gold is known to be *slightly* soluble in the salts, especially the persalts of iron. It is also *quite soluble* as gold sulphide in alkaline sulphides. It is probable, therefore, that the usual solvents of gold are iron sulphates, and especially alkaline sulphides. There is also a silicate of gold, which, according to Bischof, is slightly soluble under certain conditions.

There is abundant evidence that the auriferous quartz-veins of California have been deposited from *hot solutions.* These veins exhibit in many cases the characteristic *ribbon-structure.* They exhibit also the *water-cavities* characteristic of deposits from solutions, and the *vacuous*

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* Cazin, Newberry, etc., Report on Nacimiento Copper-Mines of New Mexico.

spaces, indicating that the solutions were *hot*. By actual experiment,* the *temperatures* at which the vacuous spaces disappear, and therefore at which the deposit took place, have been ascertained—being 180°, 212°, 350° F., and even more. Again, there can be no doubt that the associated metallic sulphides were deposited from the same solutions as the vein-stuffs, for they are completely inclosed in the latter. But the gold, as already stated (p. 250), exists as minute crystals and threads of metal *inclosed in the sulphide of iron*, and must therefore have been deposited from the same solution as the iron. It seems possible that the gold was dissolved in a solution of sulphate of iron, and that the sulphate was deoxidized, and became insoluble sulphide and precipitated; and that the gold thus set free from solution was entangled in the sulphide at the moment of the precipitation of the latter. Or else, and more probably, the gold was dissolved as sulphide along with iron sulphide in an alkaline sulphide solution and deposited by reactions 1 or 4 given on page 255, the gold, on account of its feeble affinities, giving up its sulphur at the moment of its deposit.†

There are some phenomena connected with the occurrence of gold in the iron sulphides of the *deep placers* which seem to prove the truth of this view.‡ The deep placers of California are gravel-drifts in ancient river-beds, covered up by lava-flows 100 to 200 feet thick. These placers are worked by running tunnels beneath the basaltic lava until the river-gravel is reached. Now, the waters percolating through these lava-flows and reaching the subjacent gravels are *charged with alkali* from the lava. These alkaline waters are also charged with *silica* from the same source. Hence, the *drift-wood* of these ancient rivers has all been silicified by these siliceous waters. The gravels are also in many places cemented by the same material. These percolating waters have evidently also contained *iron;* for in contact with the silicified wood is often found iron sulphide. There are two ways, in either of which we may imagine the gold to have been deposited. It may have been in solution in the iron sulphate; or else, along with the iron in

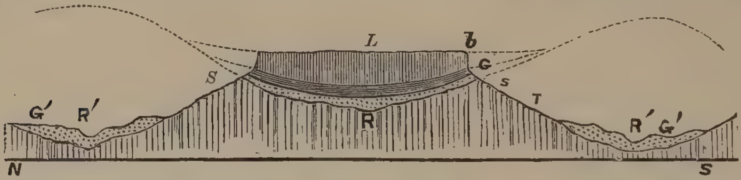

FIG. 222.—Section across Table Mountain, Tuolumne County, California: *L*, lava; *G*, gravel; *S S*, slate; *R*, old river-bed; *R′*, present river-bed.

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* Arthur Phillips, ibid.

† Gold is soluble in sodium sulphide, probably as gold sulphide.—*Becker.*

‡ Arthur Phillips, ibid.

alkaline sulphide. Following out the process on the *first* supposition, while the wood decayed it was partly replaced by silica and partly by iron sulphide produced by deoxidation of the sulphate by organic matter (p. 200). The gravel has also in some places been cemented by iron sulphide reduced from solution in a similar way. Now, both in this petrifying and in this cementing sulphide of iron is found (by solution in nitric acid) *gold:* sometimes in *rounded grains*, and therefore simply inclosed *drift-gold;* but also sometimes in *minute crystals and threads*, exactly as in the sulphide of the undecomposed quartz-vein. Evidently, this gold has been deposited from a *solution of sulphate of iron* at the moment of the reduction of the latter to a sulphide. The process was probably as follows: Percolating water oxidized iron sulphide and took it into solution as sulphate. This solution coming in contact with *drift*-gold dissolved it, but, subsequently, coming in contact with decaying organic matter, was again deoxidized and deposited as sulphide; and the gold crystallizing at the same moment is inclosed.* Or following out the process on the *second* supposition, gold sulphide in solution in alkaline sulphide, coming in contact with decaying wood, would be deposited by neutralization of the alkali along with other metallic sulphides present and be entangled with them. But, on account of its feeble affinities, the gold would give up its sulphur either to the alkaline sulphide or to the sulphide of iron and be deposited in a metallic form. Now, a similar reaction would take place in a fissure, and form a gold-bearing vein. In fact, the sub-lava gravels may be regarded as a horizontal water-way or fissure with its walls through which water circulates and deposits.

Suppose, then, we have hot water containing alkaline carbonate and alkaline sulphide, holding in solution silica and metallic sulphides, among them gold sulphide, and coming upward through a fissure. By any of the reactions on page 255, e. g., by *cooling*, silica would deposit as quartz vein-stuff and the gold would deposit with other metallic sulphides, giving up, however, its sulphur in the act of deposition, as before explained. If the alkaline waters contained no other metallic sulphide but gold sulphide, then the gold, giving up its sulphur to the alkaline sulphide, would be found in form of metallic gold inclosed in the quartz vein-stuff.

Illustrations of the Law of Circulation.—We have said that the iron sulphate comes from oxidation of sulphide, but also the sulphide from the deoxidation of the sulphate. This is only another example of a perpetual cycle of changes. Again, the gold in the veins is leached from the strata; the strata doubtless received it from the sea, for small quantities of gold have been detected in sea-water; but, again, doubtless the sea received it from the rocks, and this brings us to another perpetual cycle of changes.

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* Arthur Phillips, ibid.

But in the midst of all these changes there has evidently been an increasing concentration and availability of gold and other metals. In the strata the quantity is so small as to be undetectable; it is thence carried and concentrated in veins in a more available form; it is next set free along the backs of these veins in a still more available form; it is last carried down by currents along with other materials, neatly sorted, and deposited in *placers* in a form the most available of all.

SECTION 3.—MOUNTAINS: THEIR ORIGIN AND STRUCTURE.

Mountains are often regarded as types of permanence. We speak of the *everlasting* hills. The first lesson taught by geology is that all things, even the most stable, are slowly changing. In this section we treat of the origin, growth, maturity, decay, and death—in a word, the whole life-history of mountains.

Mountains are the glory of our earth, the culminating points of its scenic grandeur and beauty. But few recognize the fact that they are so, only because they are also the culminating points, the theatres of greatest activity, of all geological agencies. The study of mountains is therefore of absorbing interest not only to the poet and painter, but also and especially to the geologist, because it furnishes the key to many of the obscurest problems of dynamical geology.

But we are met at the very threshold of the subject by a difficulty arising from the loose use of the term *mountain*. This term is used for every conspicuous elevation above the general level of the surrounding country, whatever may be its dimensions or its mode of origin. Thus we apply it to a whole system of ranges, such as the Rocky-Mountain system, or the Andes, or the Himalayas; or to each component range of such a system, such as the Sierra or the Wahsatch; or to each prominent peak on such a range, as, for example, Mount Lyell, Mount Dana, or Mount Shasta. It is necessary, therefore, first of all, that we should define what we are going to discuss.

Definitions of Terms.—A *Mountain-System* is a great complex of more or less parallel ranges in the same general region but born at different times (polygenetic). It is a *family of mountains*. In the Rocky-Mountain system, or, as it is better called, the North American Cordilleras, we have the Colorado range (Front range), the Wahsatch range, the Basin ranges, the Sierra range, and several others. Similarly the Andes and Himalayas consist of several ranges.

A *Mountain-Range* is a single *mountain-individual* produced by *one birth-throe* (monogenetic), although both the origin and the subsequent growth is a slow process. The Sierra, the Wahsatch, the Uinta, and the Colorado Mountains are good examples.

A *Mountain-Ridge* is a subordinate part of a range, produced either by separate folds made at the same time, or by faulting, or by erosion. The Blue Ridge, the Alleghany, and the Cumberland Mountains are examples in the Appalachian range. The parallel folds of the Jura range—seen in cross-section in Fig. 227—are probably the best examples.

On mountain-ridges there are always prominent points which are called *Peaks*, whether formed by volcanic ejections like Mount Shasta or Mount Ranier, or by erosion like Mount Dana or Mount Lyell.

Mountain-systems are separated by great interior *Continental basins* like the Mississippi-river basin. *Ranges* are separated by great *interior valleys*, like Sacramento and San Joaquin Valley, separating the Sierra from the Coast range. *Ridges* are separated by *longitudinal* mountain-valleys, while the *transverse* valleys which trench the flanks of ranges or ridges head in the *passes* which separate the *peaks.*

Such is the simplest idea of mountain form, partially realized in some cases. But, to an observer looking down from a high peak, a mountain-range often seems to be made up of an inextricable tangle of ridges running and peaks standing in every conceivable direction.

Now, a scientific discussion of mountains is really a discussion of *ranges* or mountain individuals. For, on the one hand, a mountain-system is only a multiplication of such individuals belonging to the same family, and therefore adds no new element to the discussion; and, on the other, mountain ridges and peaks belong, mainly at least, to the category of mountain sculpture, not of mountain formation, and therefore are discussed later.

Greater Inequalities of the Earth-Surface.—The inequalities of the earth-surface, as already explained (page 174), are of two general kinds, the greater and the lesser. The latter belong to sculpture, and will be taken up later. Of the former there are two orders of greatness, viz., those constituting land-masses and oceanic basins, and those constituting mountain-ranges and intervening valleys. We have already discussed the former; we now take up the latter.

Mountain Origin.

Leaving aside for the present all disputed points, it is now universally admitted that mountains are *not* usually pushed up by a vertical force from beneath, as once supposed, but are formed wholly by *lateral pressure.* The earth's crust along certain lines is *crushed together* by lateral or horizontal pressure and rises into a mountain-range along the line of yielding, and to a height proportionate to the amount of mashing. But the yielding is not by rising into a hollow arch, nor into such an arch filled beneath with liquid (for in neither case could the arch support itself), but by a mashing together and in thickening and crumpling of the strata and an upswelling of the whole mass along the line of greatest yielding. That this is the immediate or *proximate* cause of the origin or elevation of mountains is plainly shown by their structure. As to the *ultimate* cause—i. e., the cause of the enormous lateral pressure—this lies still in the field of discussion. We shall discuss it briefly in its proper place.

Mountain Structure.

A mountain-range, then, may be regarded as a mass of enormously thick strata crushed together laterally and swelled up along the line of crushing. We have said that this mode of origin is revealed in its structure. We can best make this plain by an experiment. Suppose, then, we place, one atop another, several layers of any plastic substance, such as wax, so as to make together a prismatic mass, as represented in section in Fig. 223, A, and the whole resting on a smooth oiled slab of glass or steel, so that there shall be no friction or adhesion. Suppose, further, that very gentle heat be applied beneath along the middle line, so as to soften slightly this part. Of course, such softening would be greatest at the bottom, and become less and less upward; also greatest along the middle line, and become less and less outward. This is represented in the *figure* by the shading and in *nature* by the metamorphic softening, of which we will

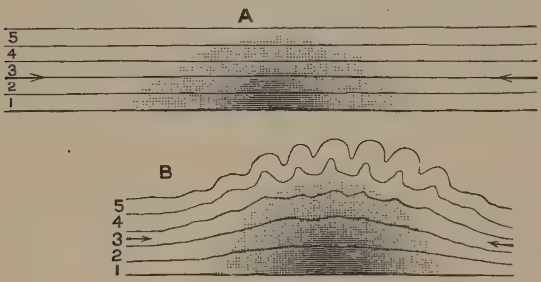

FIG. 223.

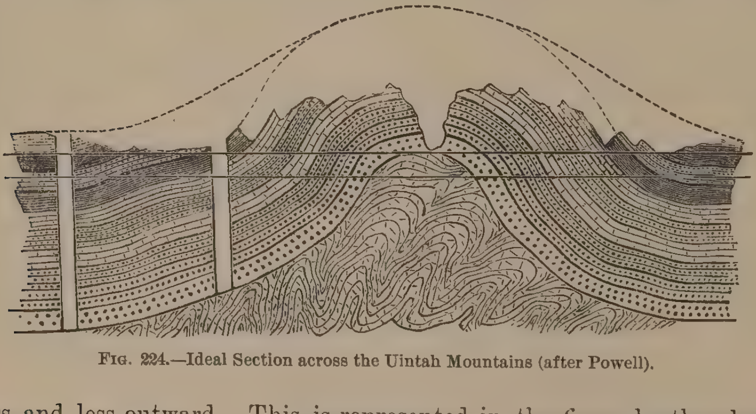

FIG. 224.—Ideal Section across the Uintah Mountains (after Powell).

speak later. Suppose, now, we place a board on each side of the prismatic mass, and press gradually together. All the layers will be

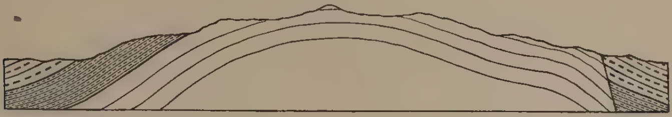

FIG. 225.—Section of Uintah Range, showing Fault.

thickened and folded, and the whole mass swelled up along the central line into something like Fig. 223, B. We have in miniature both the structure and the mode of formation of a mountain-range. In a similar way, but on a larger scale, all great mountain-ranges seem to have been formed.

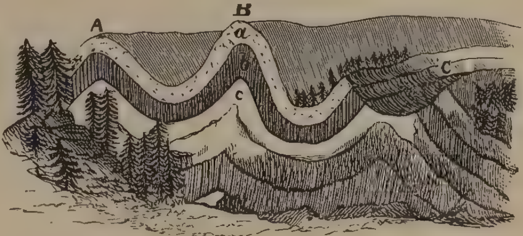

FIG. 226.—Ideal Section of Jura if unaffected by Erosion.

There would be in the experiment, and much more would we expect in Nature, some variety in the result depending upon the softness or stiffness of the strata. This it is that gives rise to different types of mountains. Sometimes the whole mass rises as *one* great fold (Fig. 224). We have an example of this in the Uintah range, only that the fold has broken down on one side, forming a great fault (Fig. 225). Sometimes and oftener there are produced several *open* folds like great earth-waves (Fig. 226). This is the case in the Jura (Fig. 227). Sometimes, and oftenest of all, there are produced many *closely appressed* folds, as in the experiment (Fig. 223, B). This is the

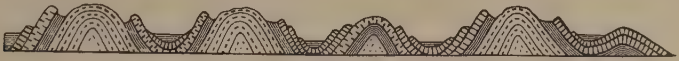

FIG. 227.—Section of Jura as modified by Erosion.

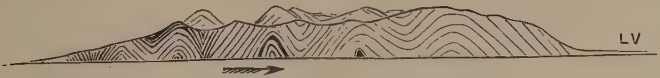

FIG. 228.—Section of Coast Range, showing Plication by Horizontal Pressure.

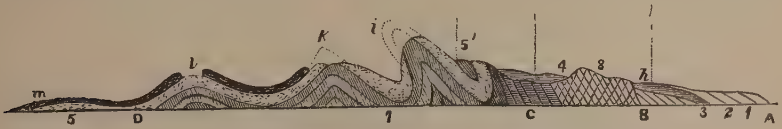

FIG. 229.—Generalized and Simplified Section of the Appalachian Chain.

case in the Coast Range of California (Fig. 228), or in the Appalachian (Fig. 229). Sometimes the mashing is so extreme that the sides are driven in under the swollen central parts, so that the strata are often reversed. This gives rise to the *fan-structures* found in many mountains, but conspicuously in the Alps (Fig. 230) and in the Pyrenees.

Proof of Elevation by Lateral Pressure alone: 1. *Folding.*—It is evident that foldings such as those represented in all the above figures, and which occur in nearly all mountains, can not be produced except by lateral pressure, and are therefore proof of such pressure. But, moreover, it can be shown that, when we take into consideration the immense thickness of mountain strata and the degree of folding, lateral pressure is *sufficient* to account for the whole elevation, without calling in the aid of any upward pushing from beneath. For example, the Coast Range of California (Fig. 228) is composed of at least five anticlines and corresponding synclines.* If its folded strata were spread out horizontally in the position of the original sediments, they would undoubtedly cover double the space. Now, supposing the strata here are only 10,000 feet thick—a very moderate estimate—in mashing to one half the extent, they would be thickened to 20,000 feet, which would be a clear elevation of 10,000 feet if they had not been subsequently eroded. According to Renevier,† a section of the Alps reveals seven anticlines and corresponding synclines, and some of these are complete over-folds (Fig. 230). We are safe in saying that Alpine strata have been mashed horizontally into one half their original extent.‡ Supposing these were originally 30,000 feet thick (they were really much thicker), this would make a clear elevation of 30,000 feet. Of course, most of this has been cut away by erosion. In the Appa-

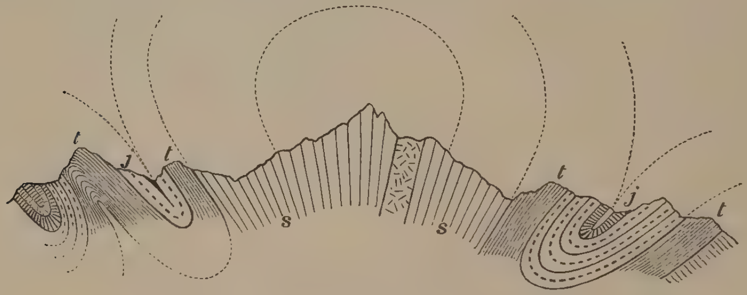

FIG. 230.—Section of a portion of the Alps.

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* American Journal of Science, vol. ii, p. 297, 1876.

† Archives des Sciences, vol. lix, p. 5, 1877.

‡ Heim., Arch., vol. lxiv, p. 122, 1878.

lachian range, according to Claypole,[*] the foldings are so extreme that in one place 95 miles of original extent have been mashed into 16 miles, or six into one, and yet the Appalachian strata are estimated as 40,000 feet thick. Cases of still greater doubling of strata upon themselves occur. In the Highlands of Scotland the strata by lateral thrust were broken and slidden one over *another for ten miles.*[†] In the Canadian Rocky Mountains there is an overthrust of seven miles, by which the Cambrian is made to override the Cretaceous, and 50 miles of strata are mashed into 25 miles (McConnell).[‡] In the Appalachians of Georgia the *Rome fault* is an overthrust which brings the Cambrian in contact with the Carboniferous and the fault under different names may be traced northward for 275 miles; and in the Cartersville thrust-fault there is an overriding of 11 miles (Hayes).[#] The manner in which this was done is illustrated on a previous page (Fig. 209). Evidently, then, the whole height of the mountains mentioned above is due to *lateral crushing alone.*

2. *Slaty Cleavage.*—But there is another phenomenon associated with mountains which furnishes additional proof, if any be necessary, viz., slaty cleavage. This is not so universal a phenomenon as folding, because the materials of strata are not always suitable for developing this structure; but where it occurs its evidence is equally convincing. We have already seen (p. 191) that this structure is always produced by mashing together horizontally and extension vertically. We have also seen that in every case of well-developed cleavage the whole rock-mass has been mashed horizontally three parts into one, and swelled up vertically one part into three. Now, again, considering the thickness of mountain strata, this is sufficient to account for the highest mountains in the world. It is true we often find slaty cleavage where there are *now* no mountains. In such cases the elevation produced by the mashing has been swept away by erosion. We find only the bones of the extinct mountains.

It was once supposed that mountains were pushed up from below by a vertically acting force. Hence came the word *upheaval* as applied to mountains. The word is still used; and there is no objection to its use, if it be borne in mind that, in mountains of the structure given above, the force of upheaval is not vertical but *lateral.*

Modifications of the Simple Ideal given above.—Thus far, in order to get a clear idea of the process and the result, we have described mountains in their simplest form, and as similar in process of formation and result to the experiment shown in Fig. 223. But in fact the final result in Nature is complicated in many ways. Some of these complications are shown in the foregoing figures of actual mountains, and have been anticipated in their descriptions. It is necessary now to discuss these more fully:

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[*] American Naturalist, vol. xix, p. 257, 1885.

[†] Geike, Nature, vol. xxix, p. 31, 1884.

[‡] Geol. Surv. of Canada, p. 33, 1886.

[#] Bull. Geol. Soc. of Am., vol. ii, pp. 144 and 147, 1891.

1. *By Fracture and Slipping.*—It is obviously impossible that such violent foldings of the strata should take place without frequent fracture and slipping of the broken parts. These fractures and faults were produced at the time of origin, or else during the growth of the range. If the mountains are very old, erosion has long since cut down the inequalities thus produced; but if the mountains are recent, they may still form conspicuous orographic features. In Fig. 231 the lower part shows the Uintah Mountains as they are, and the upper part shows the same as they would be if the eroded strata were restored. In more complex mountains the fracturing and faulting are also more complex. Fig. 232 shows the result of an actual experimental crushing of variously-colored layers of clay.

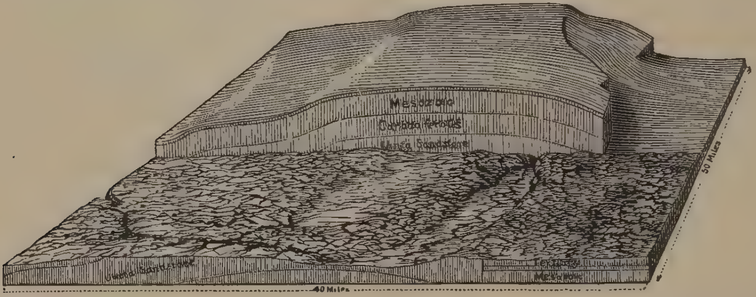

Fig. 231.—Uintah Mountains: Upper Part restored, showing Fault; Lower Part showing the Present Condition as produced by Erosion (after Powell).

2. *By Metamorphism.*—We have said that mountain strata are often of enormous thickness. We shall give abundant proof of this hereafter. But we have also seen (p. 231 *et seq.*) that the accumulation of sediments to great thickness will produce a rise of the isogeotherms—an invasion of the sediments with their included water by the interior heat, and a consequent hydrothermal softening or incomplete hydrothermal fusion of the lower parts of such accumulations. Now we find that mountain strata are nearly always more or less meta-

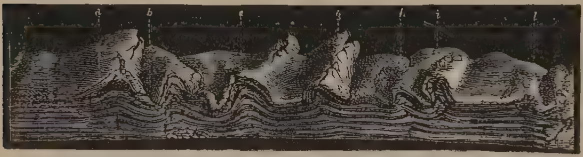

Fig. 232.—Layers of Clay folded by Lateral Pressure (after Favre).

morphic in their lower parts. Thus every great mountain-range has a *metamorphic core.* This is represented in the experimental figure (Fig. 223) by the shading.

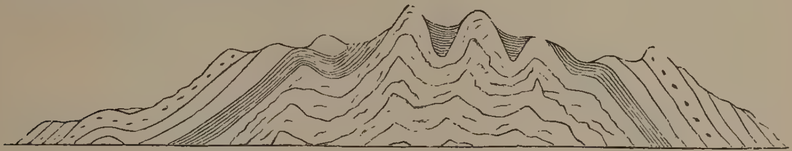

Fig. 233.—Ideal Section of a Mountain-Range.

3. *By Subsequent Erosion.*—The modifications thus far spoken of were produced at the time of preparation or else in the origin and growth of the mountain, and therefore belong to the category of mountain formation. But so soon as the mountain begins to rise, it begins to be sculptured by erosion; and when we remember that, on account of their great elevation and steep slopes, mountains must be the theatres of the greatest activity of erosion, it is evident that the metamorphic core will often be exposed by erosion along the crests. Thus the typical structure of a great mountain-range is that of a metamorphic or granitic axis emerging along the crest and flanked on each side by strata corresponding to one another. It was formerly supposed that the granitic axis was pushed up from below, breaking through the strata and appearing above them. But it is far more probable that the so-called granitic axis is only the metamorphic core formed as already explained, and exposed by subsequent erosion. Fig. 233 is an ideal of a mountain-range on this view. In this case the core is only metamorphic; and remnants of unchanged strata, caught up and left among the folds of the crests, show that these strata once extended over the top, and that the metamorphic axis is exposed only by erosion. Only carry the metamorphism a step further and the erosion a little deeper, and we have the granitic axis complete (Fig. 234).

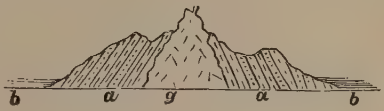

Fig. 234.

Mountains are made out of Lines of Thick Sediments.—But the question occurs, What determines *the place* of a mountain-range? The answer is, A mountain-range while in preparation—before it became a range—was a line of very thick sediments. This is a very important point in the theory of mountain origin, and therefore must be proved. The strata of all mountains, where it is possible to measure them, are found to be of enormous thickness. The strata involved in the folded structure of the Appalachian, according to Hall, are 40,000 feet thick; the strata exposed in the structure of the Wahsatch, according to King,* are more than 50,000 feet thick; the Cretaceous strata of the Coast Range, near the Bay of San Francisco, according to Whitney,† are 20,000 feet thick; and if we add to this 10,000 feet for the Eocene and Miocene strata, the whole thickness is probably not less than 30,000 feet, while the Cretaceous alone in Northern California, according to Diller, is 30,000 feet.‡ The Alpine geologists estimate the thickness of the strata involved in the intricate structure of the Alps as 50,000 feet.# The strata of Uintah, according to Powell, are 32,000 feet thick.

Now, it must not be imagined that these numbers merely represent the *general* thickness of the stratified crust; only, that in these places the strata are turned up and their edges exposed by erosion, and thus their thickness revealed. On the contrary, it may be shown that the same strata are much thinner elsewhere. The same strata which along the Appalachian range are 40,000 feet thick, when traced westward thin out to 4,000 feet at the Mississippi River. The same strata which along the line of the Wahsatch are 30,000 feet thick, when traced eastward thin out to 2,000 feet in the region of the Plains.‖ It is evident, therefore, that mountain-ranges are lines of *exceptionally* thick strata.

Mountain-Ranges were once Marginal Sea-Bottoms.—Where, then, do sediments *now* accumulate in greatest thickness? Evidently on marginal sea-bottoms, off the coasts of continents. The greater part of the washings of continents are deposited within 30 miles of shore, and the whole usually within 100 miles. From this line of thickest and coarsest deposit the sediments grow thinner and finer as we go seaward. But evidently such enormous thicknesses as 40,000 feet can not accumulate in the same place *without pari passu subsidence* such as we know takes place now whenever exceptionally abundant sedimentation is going on (p. 145). Therefore, *mountain-ranges before they were yet born*—while still in preparation as embryos in the womb of the ocean—*were lines of thick off-shore deposits gradually subsiding*, and thus ever renewing the conditions of continuous deposit.

As this is a very important point, it is necessary to stop here awhile in order to show that such was actually the fact in the case of all the principal ranges of the American Continent—i. e., that for a long time before they were actually formed, the places which they now occupy were marginal sea-bottoms receiving abundant sediments from an adjacent continent. We shall be compelled here to anticipate some things

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* Fortieth Parallel Survey, vol. iii, p. 451.

† Whitney, on Mountain-Building.

‡ American Journal of Science, vol. xl, p. 476, 1890.

Judd, Volcanoes, p. 295.

‖ King, Fortieth Parallel Survey, vol. i, p. 122.

that belong to Part III, but we hope to make statements so general that there will be no difficulty in understanding them.

1. *Appalachian.*—The history of this range is briefly as follows: At the beginning of the Palæozoic era there was a great V-shaped land-mass, occupying the region now covered by Labrador and Canada, then turning northwestward from Lake Superior and extending perhaps *to* polar regions about the mouth of Mackenzie River. This is shown on map, Fig. 269, on page 303. There was another great land-mass occupying the present place of the eastern slope of the Blue Ridge and extending eastward probably far beyond the present limits of the continent—as shown in the same figure by dotted line in the Atlantic Ocean. The western coast-line of this land-mass was the present place of the Blue Ridge. Westward of this line extended a great ocean—"the interior Palæozoic Sea." The Appalachian range west of the Blue Ridge was then the *marginal bottom of that sea.* During the whole of the Cambrian, Silurian, and Devonian, this shore-line remained nearly in the same place, although there was probably a slow transference westward. Meanwhile, throughout this immense period of time, the washings from the land-mass eastward accumulated along the shore-line, until 30,000 feet of thickness was attained. At the end of the Devonian some considerable changes of physical geography of this region took place, which we will explain when we come to treat of the history of this period. Suffice it to say now that during the Carboniferous the region of the Appalachian was sometimes above the sea as a coal-swamp, and sometimes below, but all the time receiving sediment until 9,000 or 10,000 feet more of thickness was added, and the aggregate thickness became 40,000 feet. Of course, it is impossible that such thickness could accumulate on the same spot without *pari passu* subsidence of the sea-floor. In fact, we have abundant evidence of comparatively shallow water at every step of the process—evidence sometimes in the character of the fossils, sometimes in the form of shore-marks of all kinds, sometimes in the form of seams of coal, showing even swamp-land conditions. Again, of course, the sediments were thickest and coarsest near the shore-line, and thinned out and became finer toward the open sea, i. e., westward. Finally, after 40,000 feet of sediments had accumulated along this line the earth-crust in this region gave way to the lateral pressure, and the sediments were mashed together and folded and swollen up into the Appalachian range. Subsequent erosion has sculptured it into the forms of scenic beauty which we find there to-day.

2. *Sierra.*—This was apparently the *first-born* of the Cordilleran family. Its history is as follows: During the whole Palæozoic and earlier part of the Mesozoic, there was in the Basin region a land-mass, whose form and dimensions we yet imperfectly know, but whose Pacific

shore-line was *east of the Sierra.* The Sierra region was therefore at that time the marginal bottom of the Pacific Ocean. Probably the position of this shore line changed considerably at the end of the Palæozoic. The extent of this change we will discuss hereafter. Suffice it to say now that, during the whole of this time, the Sierra region received sediments from this land-mass until an enormous thickness (how much we do not know, because the foldings are too complex to allow of estimate) was accumulated. At last at the end of the Jurassic, the sea-floor gave way to the increasing lateral pressure along the line of thickest sediments, and these latter were crushed together with complex foldings and swollen up into the Sierra. An almost inconceivable subsequent erosion has sculptured it into the forms of beauty and grandeur which characterize its magnificent scenery.

3. *Coast Range.*—The birth of the Sierra transferred the Pacific shore-line westward, and the waves now washed against the western foot of that range, or possibly even farther westward in the region of the Sacramento and San Joaquin plains. At this time, therefore, the region of the Coast Range was the marginal bottom of the Pacific Ocean. During the whole Cretaceous, Eocene, and Miocene, this region received abundant sediments from the now greatly enlarged continental mass to the eastward; until finally, at the end of the Miocene, when 30,000 feet of sediments had accumulated along this line, the sea-floor yielded to the lateral pressure, and the Coast Range was born; and the coast-line transferred to near its present position.

4. *Wahsatch.*—The physical geography of the region to the east of the Wahsatch (Plateau region) during Jura-Trias time is little known. But during the Cretaceous the region of the Wahsatch was the western marginal bottom of the great interior Cretaceous Sea (see map, Fig. 760, p. 486), receiving abundant sediments from the great land-mass of the Basin and Sierra region. This greatly increased the enormous thickness of sediments already accumulated along this line in earlier times. At the end of the Cretaceous the sediments yielded, and the Wahsatch was born. It is necessary, however, to say that both the Sierra and Wahsatch underwent very great changes of form produced by a different process and at a much later period. We shall speak of this later.

5. *Alps.*—Mr. Judd has recently shown that the region of the Alps, during the whole Mesozoic and Early Tertiary, was a marginal sea-bottom, receiving sediments until a thickness was attained not less than that of the Appalachian strata. At the end of the Eocene these enormously thick sediments were crushed together with complicated foldings and swollen upward to form these mountains and afterward sculptured to their present forms.

The same may be said of the Himalayas and nearly all other mountains. We may, therefore, confidently generalize, and say that the places now occupied by mountain-ranges have been, previous to their formation, places of great sedimentation, and therefore usually marginal *ocean-bottoms*. In some cases, however, the deposits in interior seas or mediterraneans have yielded in a similar way, giving rise to more irregular ranges or groups of mountains.

It is easy to see now why mountain-ranges so often form the *borders* of continents, and that continents consist essentially of interior basins with coast-chain rims. The view of formation of mountains, above presented, necessitates this as a *general* form, while it prepares us for exceptions in case of mountains formed from mediterranean sediments. We see also why in the case of parallel marginal ranges of the same system, such as the Sierra and Coast Ranges, these should be formed successively seaward.

In the above account of mountain-building, for the sake of clearness and brevity, we have made the process too simple. It is really much more complex. Mountains are lines of crust-weakness, and therefore have been subject to repeated movements. In the case of the Sierra, its birth was indeed at the end of the Jurassic; but it suffered another great movement at the end of the Tertiary, of which we shall have much to say hereafter. In the Coast Range the greatest movement was indeed at the end of the Miocene, but it suffered a previous movement at the end of the Jurassic and a subsequent one at the end of the Tertiary—both of them coincident with the Sierra movements. So also the Appalachians have suffered several movements. In each case we have spoken only of the greatest.

Why Thick Sediments should be Lines of Yielding.—Admitting, then, that mountains are formed by the squeezing together of lines of very thick sediments, the question still occurs, *Why does the yielding take place along these lines in preference to any others?* This is a capital point in the theory of mountain formation. The answer is as follows: We have already seen (p. 231) that accumulation of sediments causes the isogeotherm to rise and the interior heat of the earth to invade the lower portion of the sediments with their included waters. Now this invasion of heat in its turn causes hydrothermal softening or even fusion, not only of the sediments, but also of the sea-floor on which they rest. Thus a line of thick sediments becomes a line of softening and therefore a line of weakness, and a line of yielding to the lateral pressure, and therefore also a line of mashing together and folding and up-swelling—in other words, a mountain-range. As soon as the yielding commences we have an additional source of heat in the crushing itself. In addition to this, upheaval by lateral crush by the tendency to arch the strata would produce relief of gravitative pressure, and therefore fusion (p. 103). It follows from this that there is or was beneath every mountain a line of fused or semi-fused matter. This we will call the *sub-mountain liquid.* This by cooling and solidification becomes a *metamorphic or granitic core*, which by erosion forms the metamorphic or granitic axis and crest of many great mountains.

Brief History of a Mountain-Range.—The preparation for a future mountain commences by the accumulation of enormous thickness of sediment off a coast-line. This is the *embryonic condition* of the range; it is still within the womb of ocean. Next, the line of sediments yields to the ever-increasing lateral thrust, and the mountain is *born.* As soon as it appears, there begin to act upon it two opposite forces—one upheaving, the other cutting away; the one interior, the other exterior—which may be compared to the opposite processes of supply and waste in the animal body. So long as the supply exceeds the waste, the mountain *grows.* When these opposite processes are in equilibrium, the mountain is *mature.* When the waste by erosion exceeds the supply by upheaval, the mountain has entered upon its period of *decay.* Finally, the destructive forces triumph, and the mountain is swept clean away by erosion. This is *mountain-death.* We find mountains in all these stages. The Sierra, the Wahsatch, and the Coast Range are probably still growing. The Appalachian is already mature or probably entered on its period of decay. In the folded structures of the enormously thick rocks of the Archæan region of Canada we undoubtedly find the bones of extinct mountains.

Slowness of Mountain Origin and Growth.—Although, as we shall see in Part III, the formation of mountains often marks the boundaries of geological periods, and therefore, in a geological sense, the process is comparatively rapid, yet in a human sense it is always extremely slow—so slow that it may and probably is going on now under our eyes, without attracting our attention.

Age of Mountains.—The date of mountain-birth is determined by the age of the strata. It must be later than the youngest strata which enter into the folded structure of the mountain or are tilted on its flanks. Thus we say that the Appalachian was born at the end of the Coal period, because all the Palæozoic strata, including the coal, enter into the composition of its folded structure, but later strata do not. We say that the Sierra was formed at the end of the Jurassic, because these are the youngest strata which are folded and tilted on its flanks. Similarly, the Cretaceous, the Eocene, and the Miocene, are all crumpled up in the Coast Range, but the Pliocene are not. Therefore we judge that this range was formed at the end of the Miocene. To illustrate: in Fig. 234 (p. 267) it is evident that the strata *a* were first deposited in a horizontal position, then tilted and eroded, and *b* were deposited unconformably on their eroded edges. The age of this mountain, therefore, is younger than *a* and older than *b*. Sometimes several movements of lifting are revealed. Thus in Fig. 235 the strata *a* were deposited horizontally, then tilted by mountain formation and eroded, and *b* deposited horizontally and unconformably on their edges; then by a second movement *b* was lifted (and of course *a* also at a higher angle than before), and *c* was deposited unconformably on *b*.

Now, by examination of mountains in all parts of the world, it is found, as might have been expected, that all the highest mountains are comparatively young, and that the oldest mountains are of moderate altitude. The reason is obvious: young mountains are in the vigor of youth, and perhaps still growing, while the oldest mountains are in the last stages of decay. The oldest of our American mountains are the low Laurentides; they are almost gone; they are pre-Cambrian. Then follow the higher Appalachian; they are pre-Triassic. Then the still higher Sierra; they are pre-Cretaceous. To mention some foreign examples: the Alps has certainly risen 10,000 and the Himalaya 19,000 feet * since Eocene times; for so high Eocene marine strata have been found on their slopes.

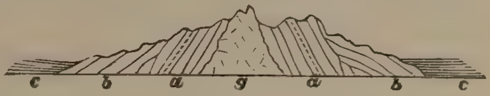

FIG. 235.

Other Phenomena associated with Mountains.—The essential phenomena demonstrating the process of mountain formation are the folded structure, the slaty cleavage, the thickness of the strata, and the position along the borders of continents. But there are other phenomena associated with mountains, which are well explained by the lateral-pressure theory, and therefore confirm the theory.

1. *Fissures, Fissure-Eruptions, and Dikes.*—The strong foldings of mountain strata inevitably produce fractures. Often these fractures extend down to the sub-mountain liquid, and this latter is squeezed out by the enormous lateral pressure, through the fissures and outpoured on the surface as great lava-floods—such as the great lava-flood of the Northwest, and the Deccan lava-flood, already described on pages 218 and 219. The outpourings on the surface may be entirely carried away by erosion, and the filled fissures through which they came may be exposed as *dikes;* or else the sub-mountain liquid may have been forced into fissures which did not reach the surface, and these also may be exposed by erosion as *dikes.* Thus lava-floods are associated with *newer* strata, and dikes with all, but especially the *older.*

2. *Volcanoes.*—Great lava-floods come up through fissures and flow off as sheets. By repeated eruptions successive sheets accumulate until the whole mass is several thousand feet thick. The lower parts of such

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* American Journal of Science, vol. xxxvii, p. 413, 1889.

lava-masses remain incandescently hot almost indefinitely. Percolating water reaching these hot interior portions develops force sufficient to eject fused matter and form volcanoes parasitic on the lava-floods; or else water may reach the sub-mountain liquid through the fissures produced by foldings and thus also produce volcanoes. Thus volcanoes also are associated with mountain-ranges.

3. *Mineral Veins.*—If the fractures do not penetrate deep enough to reach the sub-mountain liquid, then they are not filled at the time of their formation with liquid lava, but slowly afterward by deposit of mineral matter from percolating waters and form veins. Thus mineral veins are especially abundant in mountain-regions.

4. *Faults and Earthquakes.*—The walls of great fissures, as we have already seen, never remain in their original position, but always slip one on the other and thus form faults, which, in case of foldings by lateral pressure, will usually be *reverse.* Hence faults are associated with mountains. The slipping, however, will not take place all at once but *very slowly*, and yet not uniformly, but more or less *paroxysmally.* Each paroxysm will produce an earthquake. The original fracturing will also produce an earthquake. Thus earthquakes are associated with mountains, especially if the mountains are *still growing.*

We see thus the truth of the proposition with which we set out, that mountains are the theatres of the greatest activity of all geological agencies. They are first the places of greatest activity of aqueous agencies in the *form of sedimentation* in preparation for the *future* mountains; then of igneous agencies in the birth and growth of the *actual* mountain; and, finally, again of aqueous erosive agencies in sculpturing them into forms of beauty, but also in the decay and at last in the complete destruction of *former* mountains.

Cause of Lateral Pressure.—We have thus proved that the *immediate* cause of the origin and the growth of mountains is lateral pressure acting on thick sediments, crushing them together and swelling them up along the line of greatest thickness. But still the question remains, What is the *ultimate* cause, i. e., the *cause of the lateral pressure?* This, as we have already said, lies still in the domain of doubt and discussion, but the view which seems most probable may be briefly stated as follows:

In the secular cooling of the earth there would be not only unequal *radial* contraction, giving rise, as shown on page 175, to continents and ocean-basins, but also unequal contraction of the *exterior* as compared with the *interior.* At first, and for a long time, the exterior would cool fastest; but there would inevitably, sooner or later, come a time when the exterior, receiving heat from abroad (sun and space), as well as from within, would assume an almost constant temperature, while the interior would still continue to cool and contract. Thus, therefore, after a while the interior nucleus would contract faster than the exterior shell. It would do so, partly because it would cool faster, and partly because the co-efficient of contraction of a hot body is greater than that of a cooler body. Now, as soon as this condition was reached, the exterior shell, following down the shrinking nucleus, would be thrust upon itself by a lateral or horizontal pressure which would be simply irresistible. If the earth's crust were a hundred times more rigid than it is (30 times as rigid as steel, 500 to 1,000 times as rigid as granite—Woodward, Science, vol. xiv, p. 167, 1889), it must yield. Mountain-ranges are the lines along which the yielding takes place, and this yielding takes place along lines of thick sediments because these are lines of weakness.

There are several serious objections which may be brought against this view: 1. Calculations seem to show that the amount of crumpling and folding actually found in mountains is many times greater than could be produced by the contraction of the earth by *cooling*. But it may be answered (1) that the calculations take no account of the greater coefficient of contraction at high temperatures, and therefore at great depths, (2) and that there may be *other causes* of contraction besides *cooling*. For example, loss of constituent gases and vapors from the interior of the earth, through volcanic vents and fissures, has been suggested by O. Fisher (p. 102).

2. Again, it has been shown by Dutton that it is impossible that the effects of differential contraction should be concentrated along certain lines, so as to give rise to mountain-ranges without a shearing of the crust upon the interior portions, which is inadmissible if the earth be solid. Instead, therefore, of conspicuous mountain-ranges, the effects of differential contraction would be distributed all over the surface, and be wholly imperceptible. But in answer to this it may be said that there is no difficulty in the way of such shearing, and therefore of such concentration of effects along certain weakest lines, if *there be a sub-crust liquid* or semi-liquid layer, either universal or else underlying large areas of surface.

Still other objections have been raised, but these are so recent that they have not yet been sufficiently sifted by discussion to deserve mention here.* The origin of mountains by lateral pressure is a fact beyond dispute. This is the most important fact for the geologist. How the lateral pressure is produced is a pure physical question which must be left to the physicists to settle among themselves.

Another Type of Mountains—Monoclinal Mountains.—We have thus far spoken only of one type of mountains—by far the commonest type—including the greatest mountains, and long supposed the only kind. But there is another type only recently brought to light by the United States Geological Survey, the most conspicuous if not the only examples of which are found in the Basin and part of the Plateau regions. These mountains are formed in an entirely different way, viz., by the *tilting* or else the *bodily uplifting of great crust-blocks*, separated by parallel fissures. Mountains of the usual type may be called *anticlinals;* for, although often made up of many anticlines and synclines, yet, taken as a whole, they may be regarded as a grand anticline (see Fig. 233, p. 267). Mountains of this second type are called "*monoclinals.*" In mountains of the first type the faults are usually *reverse*, in the second type they are *normal.* Normal faults are extremely common everywhere, but they are rarely great enough to give rise to earth-features which deserve the name of mountains; but in the Basin region—as we have already seen, page 243—their scale is so enormous and their formation so recent that they give rise to very conspicuous orographic features. We have already, under faults (p. 243), sufficiently explained the mode of formation of the Basin ranges. We now wish to explain how the Sierra has been modified—in fact, received its present form and altitude—in this way.

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* For a completer discussion of this subject, see Theories of Mountain Origin, Jour. Geol., vol. i, p. 542, 1893.

The Sierra, as we have already seen, was formed by crushing and folding of thick sediments at the end of the Jurassic. It is probable that, by the enormous erosion of the Cretaceous and Tertiary periods, it was subsequently *cut down to very moderate altitude.* It had nearly completed one cycle of mountain life and rested. At the end of the Tertiary this great mountain-block—300 miles long and 50 to 70 miles wide—was heaved up on its eastern side, forming there a normal fault, with a displacement of probably not less than 15,000 feet.* The range was thus greatly elevated, and its crest transferred to its extreme eastern margin. This elevation commenced a new cycle of life which is still in its prime. The movement was attended with lava-flows, which ran down the western slope, filling up the old river-beds, and displacing the rivers. The displaced rivers immediately commenced cutting new beds (Fig. 8, p. 16, and Fig. 222, p. 258). That this event took place at the end of the Tertiary is shown by the fact that even the most recent Tertiary beds were covered by the lava. That the slope and therefore the height of the mountain were greatly increased at that time is shown by the fact that the rivers, seeking their base-level (p. 21), have cut their *new* beds 2,000 feet below their *old* beds, even though the time of cutting was very much less. Evidently, therefore, the present form and height of the Sierra date from the end of the Tertiary.

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* The fault-scarp is 10,000 feet, and the summit slates are deeply buried beneath Quaternary deposits at its foot.

Coincidently with this last great modification of the Sierra, the Basin ranges were also formed by crust-block-tilting. On the other boundary of the Basin region, the Wahsatch was at the same time also heaved up on its *western* side, forming there one of the greatest faults known. Therefore, so far as their *present forms* are concerned, the Sierra and Wahsatch may be said to belong to the Basin system. It is not difficult to imagine how the whole system may have been formed. At the end of the Tertiary the whole Basin region, including the Sierra on one side and the Wahsatch on the other, was lifted probably by intumescent lavas into an arch, and by *tension* split into great oblong crust-blocks. The arch broke down, the crust-blocks readjusted themselves, as explained on page 243, to form the Basin ranges, and left the abutments, viz., the Sierra and the Wahsatch, with their raw faces looking toward one another across the intervening Basin. The process and result are shown in the ideal diagram (Fig. 236). It must not be imagined, however, that this took place at once as a great cataclysm, but rather that it took place very *slowly*—the lifting, the breaking down, and the readjustment, all going on at the same time.

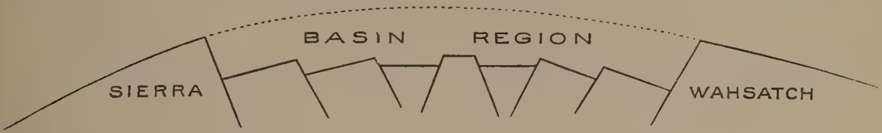

FIG. 236.—Diagram showing Probable Origin of the Basin System.

Thus, then, there are two types of mountains strongly contrasted, mountains of the one type are formed by lateral *pressure and crushing*, of the other type by lateral *tension and stretching*. The one gives rise mainly to reverse faults, the other always to normal faults. Mountains of the one type are formed by upswelling of thick sediments, those of the other type by irregular readjustment of crust-blocks. Mountains of the one type are *born of the sea*, those of the other type are born *on the land*. We find examples of the one type in nearly all the greatest mountains everywhere, but especially in the Appalachian, the Alps, and the Coast Range. The best examples, perhaps the only examples, of the other type are the Basin ranges. Some mountains, as the Sierra, the Wahsatch, and certainly *some* of the Basin ranges, belong to both types. In their origin, they have been formed in the first way, but afterward have been modified by the second way. Thus the first is the fundamental method, and the second only a modifying process.*

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* On this whole subject see papers by the writer, American Journal of Science, vol. xix, p. 176, 1880; vol. xxxii, p. 167, 1866; and Journal of Geology, vol. i, p. 542, 1893.

Mountain Sculpture.

As soon as a mountain-range lifts its head above the general level of sea or land, it is immediately attacked by erosion. All the grand and beautiful forms of mountain scenery are due to erosive sculpturing. The amount carried away is always enormously great, usually many times greater than what remains. In Fig. 231 (p. 266) we have in the upper part the Uintah Mountain with its strata restored, i. e., as it would be if never ravaged by erosion; in the lower part we have it as it now exists. The extreme thickness removed is about 25,000 feet, while only about 8,000 feet remain, for the highest peaks are now only 10,000 to 12,000 feet hight. In the Appalachian—an older mountain—probably a much larger proportion has been carried away. The amount in all cases is so great as to obscure the origin of mountains and to confuse the use of the term mountain. Hence some have divided mountains into two kinds, viz., mountains of *upheaval* and mountains of *erosion*, and some have even gone so far as to say that mountains are mere remnants of denuded continents—the prominent points of a differential erosion. But it is best to keep distinct in the mind mountain *formation* and mountain *sculpture*. They are both equally important in the final result. If igneous forces do the *rough hewing*, aqueous forces do the *shaping* into forms of beauty. When we view mountains from a distance, the blue, cloud-like bank which we see on the horizon is the result of igneous agencies; but when we are among mountains all that we see—every ridge and peak and valley—all that constitutes scenery—is the result of aqueous agencies.

Sculptural Forms.—The mode of mountain *formation* is more or less concealed in internal structure; but the forms developed by *sculpture* lie on the surface, and are easily understood, and yet they often reveal structure to the careful observer. A knowledge of these sculptural forms gives additional charm to mountain travel. They are almost infinitely diversified; yet a few of the most common and conspicuous may be given as examples. These forms are not all confined to mountains; some of them are the general forms of highland erosion; but they are most conspicuous in mountain-regions.

1. *Horizontal Strata.*—(*a*) These, if sufficiently *firm*, give rise to *table-forms*, the top of the table being determined by a slab of hard stratum, such as sandstone or grit, or by a lava-flow. In the latter case, the horizontal lava-blanket gives rise to tables, whatever be the position of the underlying strata. Good examples of this form are

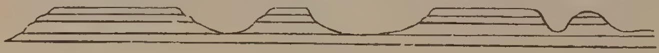

FIG. 237.

found in Illinois (Fig. 237), in Tennessee (Fig. 238), in the *mesas* of the Plateau region (Fig. 10, p. 17), and in Table Mountain, of California (Fig. 239).

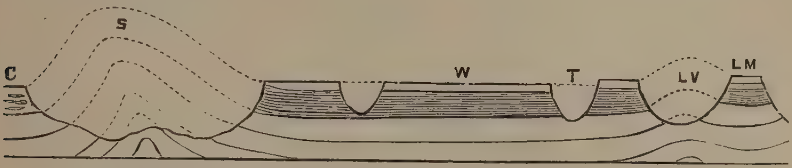

FIG. 238.—Section across Cumberland Plateau and Lookout Mountain, Tennessee.

(*b*) But if the horizontal strata are *soft*, interstratified sands and clays, their erosion gives rise to fantastic castellated forms of peaks, turrets, etc., such as are found in the *Bad Lands* of the Plains and Plateau region, which are the almost unlithified deposits of the Tertiary lakes (Fig. 240).

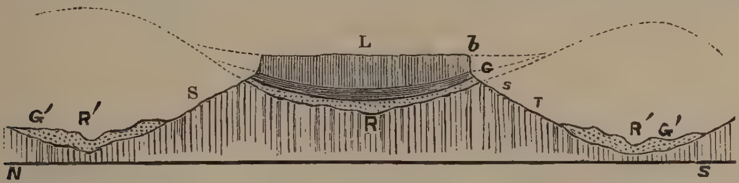

FIG. 239.—Section across Table Mountain, Tuolumne County, California: *L*, lava; *G*, gravel; *S S*, slate; *R*, old river-bed; *R*′, present river-bed.

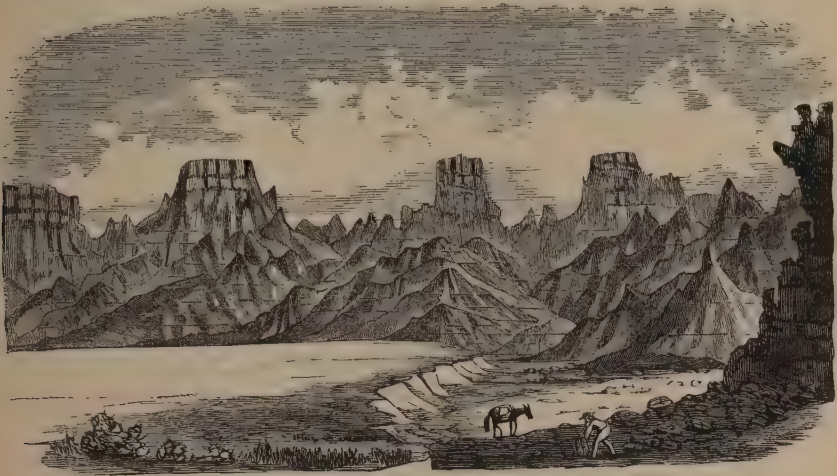

FIG. 240.—Mauvaises Terres, Bad Lands (after Hayden).

2. *Gently-undulating Strata.*—These give rise to synclinal ridges and anticlinal valleys. This is well shown in diagram (Fig. 241) and

in the subjoined section of the Appalachian coal-field in Pennsylvania (Fig. 242). This is usually explained by supposing that the backs of the anticlinals have been broken or loosened by *tension* in bending; while the synclinals have been hardened by lateral pressure—and therefore the anticlinals have yielded more easily to erosion. But Prof. Davis has shown* that such a supposition is at least not necessary. For example: if we have a series of undulating strata, some hard and some soft (Fig. 243), and well raised above base-level, the erosion will be most rapid on the anticlines, and the hard stratum (*a*) will be reached and cut through first *there.* As soon as the soft stratum beneath is reached the erosion will be still more rapid, and valleys will be formed. This will be understood by careful inspection of the figure.

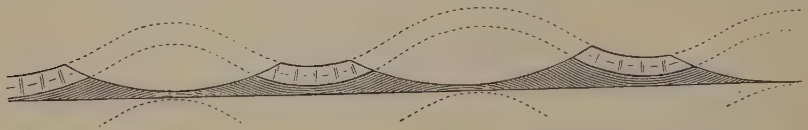

Fig. 241.—Diagram showing Synclinal Ridges and Anticlinal Valleys (after Nöe and De Margerie).

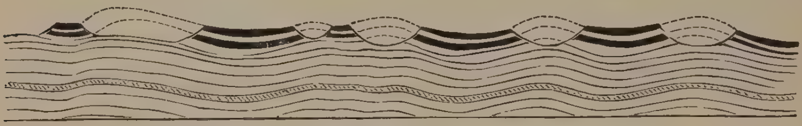

Fig. 242.—Section of Coal-Field of Pennsylvania (after Lesley).

3. *Strongly-folded or Highly-inclined Outcropping Strata.*—These give rise to sharp ridges and valleys, the ridges being determined by the outcrop of a hard stratum. Fig. 244 is an ideal diagram, showing how such ridges are formed by erosion. In the Rocky Mountains, where they are finely shown on the flanks of the mountains, they are called "*hog-backs.*" Fig. 241 represents this form of sculpture as it often appears. It is seen that every ridge is formed by outcrop of a hard

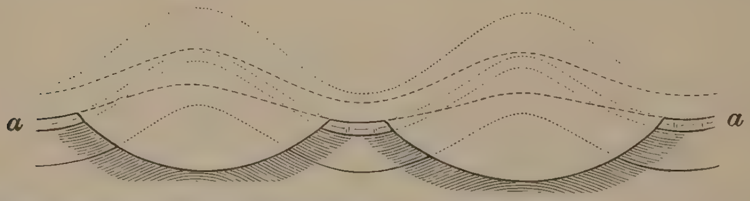

Fig. 243.—Ideal Diagram showing how, according to Davis, Synclinal Ridges are formed: full lines, *actual* surfaces and structure; dotted lines, original surfaces and structure; broken lines, former erosion-surfaces.

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* Science, vol. xii, p. 320.

sandstone, which has resisted erosion more than the intervening strata. Beautiful examples of this form are seen in parts of the Appalachian.

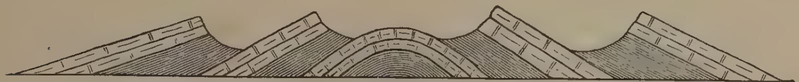

Fig. 244.—Ideal Section across an Eroded Fold, consisting of Alternating Soft and Hard Strata (after Nöe and De Margerie).

Standing on the top of Warm Springs Mountain, Virginia, ten or twelve parallel ridges may be counted, each with long slopes on one side and steep slopes on the other, like billows ready to break. The crest of each ridge is determined by the outcrop of a hard sandstone. Such ridges may be formed either by the outcrop of *successive* sandstones,

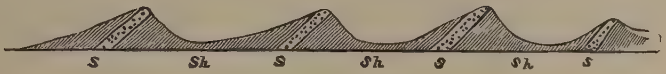

Fig. 245.—Parallel Ridges.

as in Fig. 245, or else by the successive outcrop of the *same* sandstone, as in Fig. 246.

In ridges formed in this way the relative angle of slope on the two sides of the ridges will depend on the dip of the strata. If the strata be vertical, the two slopes will be equal. If the strata are inclined, the longer slope will be on the side toward which the strata dip; and the difference of the two slopes will increase as the angle of dip becomes less. This is shown in Fig. 247 (*a*, *b*, and *c*). Finally, one slope may coincide with the face of the hard stratum, as in Fig. 244. This case, therefore, passes by insensible gradations into the next, viz.:

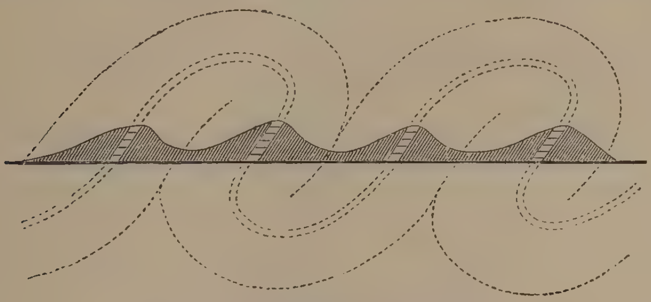

Fig. 246.—Parallel Ridges in Folded Strata.

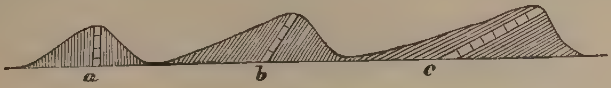

Fig. 247.

4. *Gently-inclined, almost Level Strata.*—These, by erosion, perhaps under peculiar climatic conditions, give rise to a succession of broad, nearly level tables, coincident with the face of a hard stratum, terminated each by a vertical or nearly vertical cliff. This form of

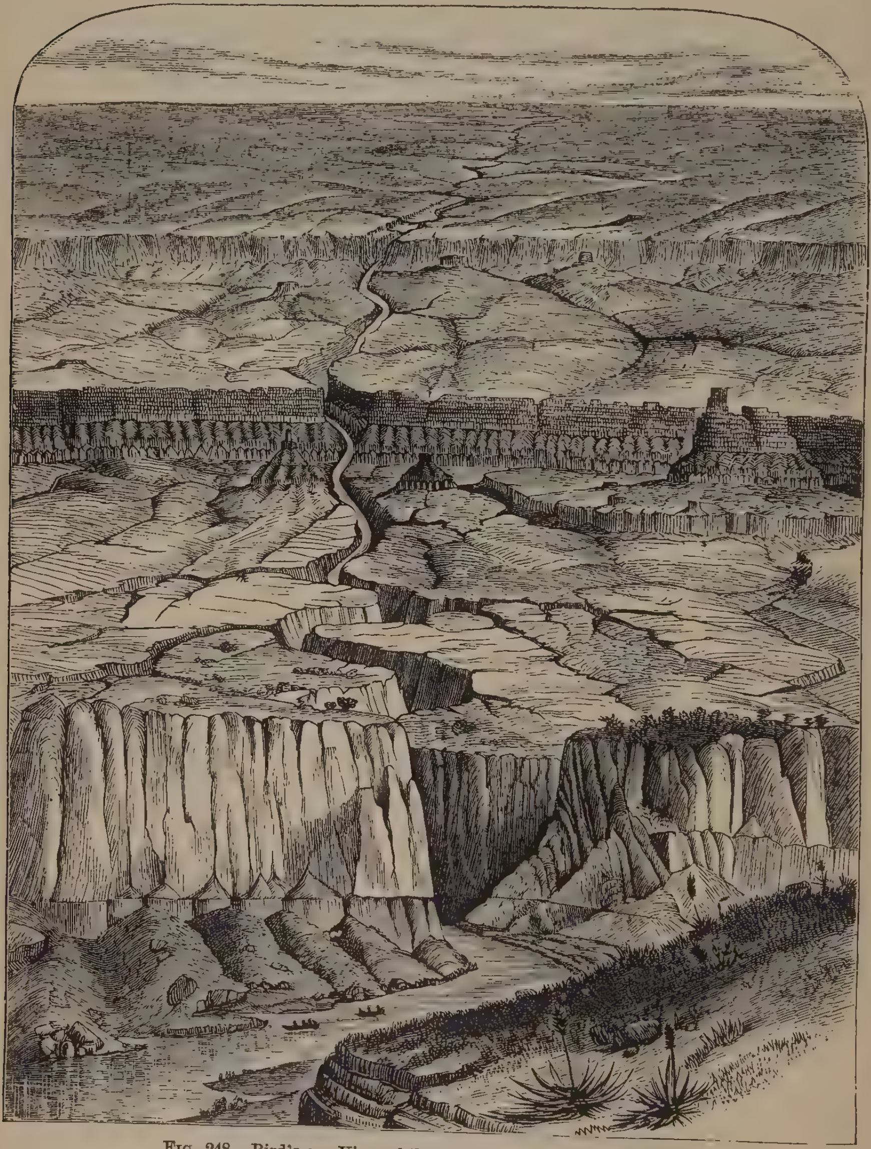

FIG. 248.—Bird's-eye View of the Terrace Cañon (after Powell).

sculpture is developed on a magnificent scale in the Colorado Plateau region. Fig. 248 is a bird's-eye view of three such tables, each 20 to 60 miles wide, and terminated by cliffs 1,500 to 2,000 feet high. Fig. 249 is an ideal section of such tables and cliffs—the dotted lines showing the portion carried away by erosion. It is evident that the drainage of each table is against the cliff; and every cliff, therefore, recedes partly by under-cutting by a river and partly by rain-wash on its face. In some cases, where the lifting of the strata was dome-like, the receding cliffs are circular, producing thus titanic amphitheatres, 100 or more miles across, with cliff-benches 1,000 to 2,000 feet high.* How slow the lifting of the strata in this region must have been is shown by the fact that the Green River runs *against the slope of the strata*, cutting its cañon deeper to the edge of the cliffs, as shown in Fig. 248. Evidently the strata were lifted athwart the course of the river, but so slowly that the river cut as fast as the strata lifted.

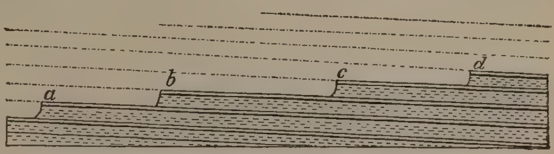

FIG. 249.—Dotted lines show material carried away by erosion.

Migration of Divides.—If the slopes on the two sides of a divide are equal, the position of the divide remains stationary; but if one slope be steeper than the other, then by the greater erosion on the steeper slope the divide will move steadily toward the gentler slope. Thus, the rivers on the steeper slope continually increase their drainage areas by appropriating from the other side. Examples of this may be found in nearly all mountains, but especially in those of the monoclinal type, and in all ridges, but especially in the case of hog-backs (Figs. 244, 245). The recession of plateau cliffs is only an extreme case under this law.

5. *Metamorphic and Granitic Rocks.*—Sculptural forms in these are usually irregular, and can not be reduced to a simple law. But, in some cases, peculiar forms are traceable to peculiar structure. Thus, for example: in and about the Yosemite Valley two kinds of forms are found, viz., (*a*) *perpendicular* cliffs and towers and spires of the valley itself; and (*b*) rounded domes abundant in the high region about the valley. The one is the result of a *rough*, imperfect *vertical cleavage* of the

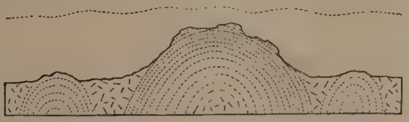

FIG. 250.—Ideal Section showing Dome-structure. Dotted line above shows original surface.

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* Dutton, High Plateaus of Utah, p. 19.

rock; the other of a *concentric structure* on a huge scale, usually undetectable in the sound rock, but brought out by weathering. This is shown in the diagram (Fig. 250).

6. *The Kind of Agent.*—It is probable that the *nature* of the erosive agent, whether as *rain and rivers* or as *snow and glaciers*, also determines peculiar scenic forms. It is probable that the former tend more to rounded summits and ridges and V-shaped gorges, the latter to sharp summits (*aiguilles*) and comb-like divides and broad U-shaped valleys.

CHAPTER VI.

DENUDATION, OR GENERAL EROSION.

As a fit ending of Part II, and preparation for Part III, in which the idea of *time* is the underlying element, it seems appropriate to make some rough estimate of the amount of general erosion which has taken place in the history of the earth, and of geological time based thereon.

The term *denudation* is used by geologists to express the general erosion which the earth-surface has suffered in geological times. The correlative of denudation is *sedimentation*, and the amount of denudation is measured by the amount of *stratified rocks.*

Agents of Denudation—The agents of erosion, as we have already seen in Part I, are: 1. *Rivers*, including under this head the whole course of rainfall on its way back to the ocean whence it came; 2. *Glaciers*, including under this head not only glaciers proper, but moving *ice-sheets*, such as now exist in polar regions, and in the Glacial epoch extended far into now temperate regions, and also moving snow-fields, for it is probable that all extensive snow-fields and snow-caps are in motion; 3. *Waves* and *tides;* and, possibly, 4. *Oceanic currents.*

Oceanic currents usually run on a *bed* and between *banks* of still water, and therefore produce no erosion. It is possible, however, that a rising sea-bottom may be eroded by this agent; but as we have no knowledge of such effects, we are compelled to omit this from our estimate of the probable rate of denudation. The action of *waves and tides* is violent and conspicuous; yet these agents are so entirely confined to the shore-line that their aggregate effect is but a small fraction of the whole erosion. Prof. Phillips has shown * that, taking the coast-lines of the world as 100,000 miles, and making the extravagant estimate that the average erosion along this whole line is equal to that of the English coast, or one foot per annum of a cliff one hundred feet high, still the aggregate wave-erosion is far less than river-erosion, being equivalent to a general land-surface erosion of only $\frac{1}{2000}$ of an inch per annum, or $\frac{1}{12}$ of that which is now going on over the hydrographical basin of the Ganges, and $\frac{1}{5}$ of that going on in the basin of the Mississippi. *Glaciers* and rivers, therefore, are the great agents of erosion. The one takes the place of the other, according as falling water takes the form of *rain* or *snow;* both come under the general head of circulating meteoric water. In a general estimate of the rate of denudation we may, therefore, without sensible error, regard it as the work of circulating meteoric water.

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* Life, its Origin and Succession, p. 130.

Again, although it is probable that the erosive power of glaciers is greater than that of rivers, yet their action is so much more local, both in *time and space*, that we believe we may take the average rate of river-erosion as a fair representative of the average rate of denudation.

Amount of Denudation.—A mere glance at the figures below will show in a general way the manner in which geologists estimate the amount of denudation in certain regions. In almost all countries, especially in mountain-regions, we find slips varying from a few feet (Fig. 251) to many thousands of feet perpendicular (Fig. 231). There are slips in the Appalachian chain which are estimated to be 8,000 and even one 20,000 feet, in the Uintah 20,000, in the Wahsatch 40,000 feet, perpendicular. And yet in most cases the escarpment, which would otherwise exist, is completely cut away, so that no surface indication of the slip exists. Evidently in such cases there must have been erosion on the elevated side, at least equal to the amount of slip, and probably much greater. The dotted line represents the probable original surface.

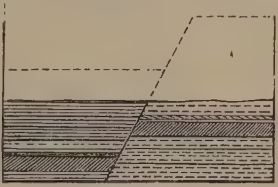

FIG. 251.

Sometimes the horizontal strata of isolated mountain-peaks corresponding to each other (mountains of erosion) show that these are but scattered fragments of a once high plateau, which has been removed by erosion, as shown in the annexed figure (Fig. 252) and in many of the figures on pages 282 and 283. In such cases the erosion must have been at least equal to the height of the peaks, and may have been to any extent greater. The accompanying section across Middle Tennes-

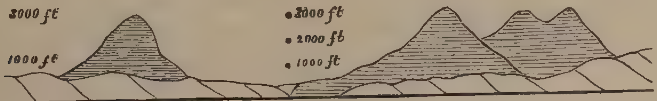

FIG. 252.—Denudation of Red Sandstone, Northwest Coast of Ross-shire, Scotland.

see shows a vertical erosion of 1,200 to 2,400 feet, over the whole valley of Middle Tennessee, which is sixty miles across and one hundred miles long. In most cases the removed matter is not so easily estimated as in those mentioned. The strata in mountain chains are usually folded in a very complex way, and then denuded. But the ideal restoration of these may be effected, and the amount of erosion approximately estimated. Figs. 254 and 255 are sections across the mountainous parts of England, as restored by Prof. Ramsay.

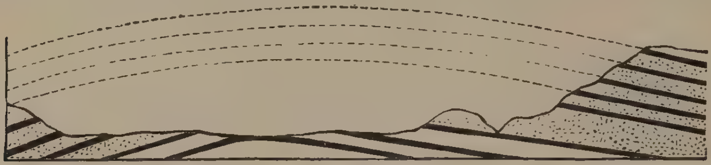

FIG. 253.—Section across Middle Tennessee. The dotted lines show the amount of matter removed.

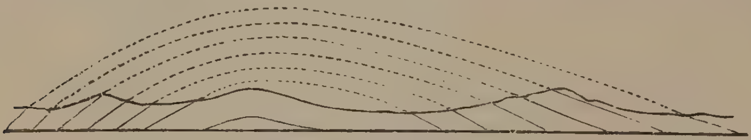

FIG. 254.—Section through Portions of England.

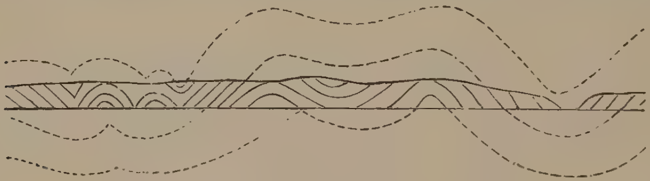

FIG. 255.—Section through Portions of England.

Average Erosion.—By these methods Prof. Ramsay estimates the denudations over many portions of England to be not less than 10,000 to 11,000 feet in thickness.* Over the whole Appalachian region the denudation has probably been enormous, in some places 8,000 to 20,000 feet. Over the whole region of the high Sierra Range, as we have shown,† erosion has removed the whole of the Jurassic and Triassic slates, and bitten deep into the underlying granite. The thickness of these slates is not known, but it must be many thousand feet. In the Uintah Mountain region, according to Powell, over an area of 2,000 square miles, an average thickness of three and a half miles has been taken away (Fig. 256), the extreme thickness removed being nearly five miles. From the Wahsatch have been removed 32,000 feet, or six miles thickness of strata (King). Over the whole Colorado Plateau

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* Geological Observer, p. 819.

† American Journal of Science and Arts, vol. v, p. 325.

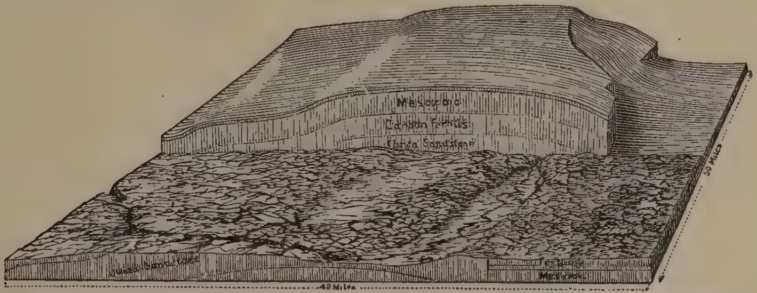

FIG. 256.—Uintah Mountains—Upper Part restored, showing Fault; Lower Part showing the Present Condition as produced by Erosion (after Powell).

region the succession of cliffs, separated by broad tables (Fig. 249), shows enormous erosion. The average erosion over the whole region has been estimated by Powell and Dutton as 6,500 feet; and the extreme general erosion, not including the cañon-cutting, as 11,000 feet. The whole of this immense mass has been removed, too, since the middle Tertiary.

It seems impossible to avoid the conclusion, therefore, that the *average erosion* over all present land-surfaces has been at least several thousand feet.

There is another mode of estimating the average erosion, viz., by the average thickness of stratified rocks. The *débris* of erosion is carried down into seas and lakes, and forms strata, and the amount of stratified rocks becomes thus the measure of the erosion; the average thickness of sediments, if they had been spread over an equal area, would be an accurate measure of the average thickness removed by erosion. Now, the stratified rocks are in some localities 10,000 feet, 20,000 feet, and sometimes 40,000 and 50,000 feet thick. They are scarcely ever found less than 2,000 or 3,000 feet. It is certain, therefore, that the average thickness of strata over the whole known surface of the earth is not less than several thousand feet. Let us take it at only 2,000 feet. But the area of sedimentation, the sea-bottom, is now, and has probably always been, at least three times the area of erosion, the land-surface. Thus an average of 2,000 feet of strata would require an average erosion of 6,000 feet.

Estimate of Geological Times.—There are many facts connected with geology, especially the facts of evolution, which can not be understood without the admission of inconceivable lapse of time. For this reason it is important that the mind should become familiarized with this idea. It will not be out of place, therefore, to make a rough estimate of time based upon the amount of erosion.

We have already seen (p. 11) that, taking the Mississippi as an average river in erosive power (it is probably much more than an average), the rate of continental erosion is *now* about one foot in 5,000 years. At this rate, to remove an average thickness of 6,000 feet would require 30,000,000 years.*

Some may object to this estimate, on the ground that geological agencies were *once* much more active than *now*. It is *probable* that this is true of igneous agencies, since these are determined by the *interior heat* of the earth, and this has evidently been decreasing. It is probable also that this is true of the *chemical* agencies of water in disintegrating rocks and forming soils, since chemical effects are also usually increased by heat. But there is good reason to believe that the *mechanical* agencies of water, i. e., its *erosive power*, has been constantly increasing with the course of time, and are greater now than at any previous epoch except the Glacial epoch.

For observe: The erosive power of water is determined entirely by the *rapidity of circulation of air and water*, and this is determined by *the diversity of temperature* in different portions, and this in its turn *by the size of continents and the height of mountains.* Continents and seas are two poles of a circulating apparatus—at one pole is condensation, at the other evaporation. In proportion to condensation are also evaporation and circulation. Now, there is good reason to believe that, amid many oscillations, there has been throughout all geological times a constant increase in the size of continents and the height of mountains. If so, then the circulation of air and water has been becoming swifter and swifter; the life-pulse of our earth has beaten quicker and quicker, and therefore the waste and supply (erosion and sedimentation) have been greater and greater.†

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* The above estimate takes the *average* thickness of strata, and supposes it spread evenly over the whole sea-bottom. This is strictly admissible only if we suppose, with Lyell, that land and ocean have often changed places, so that every portion of earth-surface has received sediments. But if, as is now most generally believed, the ocean-basins have remained substantially unchanged, and sediments have accumulated almost wholly on their margins, then we must, it is true, make our measuring rod, i. e., the rate of sedimentation, much greater, but we must also take the sum of the *extreme* thickness of strata in different localities, as the thing to be measured. We, therefore, make another estimate, on this basis, following Mr. Wallace. Taking the whole land-surface (erosion area) at 57,000,000 square miles, and the sedimentation area as thirty miles wide along a coast-line of 100,000 miles (=3,000,000 square miles), then with an erosion-rate of one foot in 3,000 years, instead of 5,000 years, the sedimentation rate would be nineteen feet in the same time, or one foot in 157 years. But the extreme thickness of strata is at least 177,000 feet. This would take 28,000,000 years.—(Wallace, Island Life, p. 210.)

† It is possible that the erosive effect of tides in earliest geological times, far greater than now, on account of the greater proximity of the moon, is an element which should not be neglected (Nature, vol. xxxv, p. 79). But this probably belongs to a time antecedent to the recorded history of the earth.

We therefore return to our estimate of 30,000,000 years with greater confidence that it is even far within limits of probability. For, 1. We have taken the average thickness of strata at 2,000 feet, while it is probably much more. 2. We have taken the Mississippi as an average river, and therefore the present rate of general erosion as one foot in 5,000 years: it is probably much less. 3. We have taken the rate of erosion in previous epochs as the same as now, while it it is probably much less, for two reasons: 1. The land-surface to be eroded was smaller; and 2. The erosive power of water was less. Taking all these things into consideration, the time necessary to produce the structure which we actually find is enormously increased.

But even this gives us no adequate conception of the time involved in the geological history of the earth. For rocks disintegrated into soils, and deposited as sediments, are again reconsolidated into rocks, lifted into land-surfaces, to be again disintegrated into soils, transported and deposited as sediments. And thus the same materials have been worked over and over again, perhaps many times. Thus the history of the earth, *recorded* in stratified rocks, stretches out in apparently endless vista. And still beyond this, beyond the *recorded* history, is the infinite unknown abyss of the *unrecorded*. The domain of Geology is nothing less than (to us) inconceivable or infinite time.*

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* Some physicists have indeed set a much lower limit to the age of the earth, but George Darwin has recently admitted that the data on which the calculations are based are wholly unreliable (Nature, vol. xlviii, p. 486, 1893). Geologists are therefore left free to make their own calculations on their own data.

PART III.

HISTORICAL GEOLOGY;

OR, THE HISTORY OF THE EVOLUTION OF EARTH-STRUCTURE AND OF THE ORGANIC KINGDOM.

CHAPTER I.

GENERAL PRINCIPLES.

Geology is the history of the evolution of earth-forms, earth-structure, and earth-inhabitants. There are certain laws underlying all development—certain general principles common to all history, whether of the individual, the race, or the earth. We wish to illustrate these general principles in the more unfamiliar field of geology by running a parallel between the history of the earth and other more familiar forms of history.

1. All history is divided into *eras*, *ages*, *periods*, *epochs*, separated from each other more or less trenchantly by great events producing great changes. In written history these are treated, according to their importance, in separate volumes, or separate chapters, sections, etc. So *earth-history* is similarly divided into geological *eras*, *ages*, *periods*, etc.; and these have been recorded by Nature in separate *rock-systems*, *rock-series*, *rock-groups*, and *rock-formations*. In geology these terms, both those referring to divisions of *time* and those referring to divisions of *record*, are unfortunately loosely and interchangeably used. We shall strive to use them as definitely as possible, the *eras* and the corresponding *rock-systems* being the primary divisions, and the others subdivisions in the order mentioned.

2. In all history successive eras, ages, periods, etc., *usually graduate* insensibly into each other, though sometimes the change is more rapid and revolutionary. In individual history childhood usually graduates into youth, and youth into manhood; yet sometimes a remarkable event determines a more rapid change. In social and political life, too, successive phases of civilization embodying successive dominant principles usually graduate into each other; yet great events have some-

times determined exceptionally rapid changes in the direction or the rate of movement. So also is it in geological history. The eras, periods, etc., usually shade more or less insensibly into each other; yet there have been times of comparatively rapid or revolutionary change. In all history there are periods of comparative quiet, during which forces of change are gathering strength, separated by periods of more rapid change, during which the accumulated forces produce conspicuous effects.

3. Ages, periods, etc., in all history, whether individual, political, or geological, are determined by the rise, culmination, and decline of successively higher dominant forces, principles, ideas, functions. Thus, in individual development, we have the culmination, first, of the nutritive functions; then of the reproductive and muscular functions; and, last, of the cerebral functions. And in mental development, also, we have the culmination, first, of the *perceptive* faculties, and memory; then, the imaginative and æsthetic faculties; and, last, the reflective faculties; the first gathering and storing material, the second vivifying it, the third using it in productive mason-work of science. In social history, too, the successive culminations of different phases of civilization have been the result of the introduction and culmination of successive dominant principles or ideas—of successive social forces or functions. So has it been in geological history. The great divisions of time, especially what are called *ages*, are characterized by the introduction and culmination of successive dominant classes of organisms, for these are the highest expression of earth-life. Thus, in geology, we have an age of mollusks, an age of fishes, an age of reptiles, in which these were successively the dominant class.

But since (Law 2) successive ages graduate more or less into and overlap each other, we might expect, and do indeed find, that the characteristics of each age commence in the preceding age. Each age is foreshadowed in the previous age. The same is true of all history. We may call this the *Law of Anticipation.*

4. In all history, at the close of an age, the characteristic dominant principle or class declines, but does not perish. It only becomes subordinate to the succeeding dominant class or principle. Thus, to illustrate from individual history: in youth, the characteristic faculties of childhood, viz., perception and memory, decline, and become subordinate to the higher faculty of imagination, and this in turn becomes subordinate to the still higher faculty of productive thought; and thus the whole organism becomes higher and more complex, each stage of development including not only its own characteristic, but also, in a subordinate degree, those of all preceding stages. The same is true of social history. Each stage of social development absorbs and includes the social principles and forces characteristic of previous stages, but

subordinates them to the higher principles which form its own characteristic, and thus the social organism becomes ever higher, more complex, and varied.

So it is also in geologic history. When the dominance of any class declines at the end of an age, the class does not disappear, but remains subordinate to the next succeeding and higher dominant class, and the organic kingdom, as a whole, becomes successively more and more complex and varied. This is graphically represented by the accompanying diagram, in which we have five successive ages determined by the culmination of as many successive dominant classes.

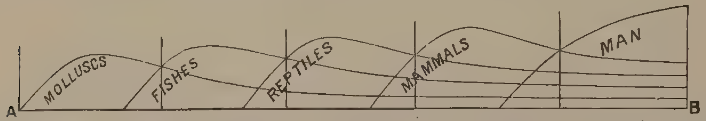

FIG. 257.—Diagram illustrating the Rising, Culmination, and Decline of Successive Dominant Classes, and the Increasing Complexity of the whole.

5. There are two modes of determining and limiting eras, ages, periods, etc., in geology, viz., unconformity of the rock-system and change in the life-system. In written human history, the divisions of time are recorded in separate volumes, chapters, sections, with boards or blank spaces between. These divisions in the record ought to correspond to conspicuous changes in the character of the most important contents. So, in the history of the earth, the rock-systems, rock-series, rock-formations, are volumes, chapters, sections, respectively, more or less completely separated from each other by unconformity, indicating blanks in the known record; and the most important changes in the contents, i. e., in the life-system, ought to, and usually do, correspond with the unconformity of the rock-system. But if there should be (as there is in some limited localities) a discordance between these two, we should follow the life-system rather than the rock-system, the contents rather than the artificial divisions of the record.

6. As in human history there is a general onward movement of the race, and yet special modifications in character and rate in each country; so in geology there has been a general march of evolution of the whole earth and the organic kingdom, and yet special modifications in character and rate in each continent, and to a less extent in different portions of the same continent. The great eras, ages, and periods, belong to the whole earth alike, and are the same in all countries, but the epochs and the smaller divisions of time, though similar, are probably not contemporaneous in different countries. This fact has probably been too much overlooked by geologists. The term *homotaxy* is used to express *identity in the stage of evolution*, as *synchronism* is used for identity of *time.*

Great Divisions and Subdivisions of Time.—Eras.—It is upon these principles that geologists have established the divisions of *time* and the corresponding divisions of *strata*.

The whole history of the earth is divided into five eras, with corresponding rock-systems. These are: 1. *Archæozoic** era, embodied in the Archæan system; 2. *Palæozoic*† era, embodied in the Palæozoic system; 3. *Mesozoic*‡ era, recorded in the Mesozoic system; 4. *Cenozoic*,# recorded in the *Tertiary* and *Quaternary* systems; and, 5. The *Psychozoic* era, or *era of Mind*, recorded in the *recent* system.

These grand divisions, with the exception of the last, are founded on an almost universal unconformity of the rock-system, and a very great and apparently sudden change in the life-system, a change affecting not only species but also genera, families, and even orders. Between the *last* and the preceding, it is true, neither the unconformity of the rock-system nor the change in the life-system is so great as in the others; but the introduction of *man* upon the scene and the sweeping changes which are now going on through his agency are deemed sufficient to make this one of the grand divisions of time.‖

We have already seen (p. 187) that unconformity is the result of deposit of strata on old eroded land-surfaces, and that it therefore always indicates an *oscillation* of the crust, and an emergence and submergence of land. In every such case, as already explained, a portion of the record is lost, which may or may not be recovered elsewhere. It is certain that if the lost leaves could be all recovered, and the record made complete, the suddenness of the break in the life-system would disappear. Nevertheless, it is also certain that these general unconformities indicate times of great change in physical geography, and therefore of climate, and therefore of rapid changes of organic forms; and therefore, also, they mark the natural boundaries of the great divisions of *time*.

Ages.—Again, the whole history of the earth is otherwise divided into seven *ages*, founded, with perhaps the exception of the first, on the culmination of certain great classes of organisms. These are: 1. The *Archæan* or *Archæozoic Age*, represented by the Archæan system of rocks; 2. The *Age of Mollusks*, or *Age of Invertebrates*, represented by the Cambrian, Ordovican, and Silurian rocks; 3. The *Age of Fishes*, represented by the Devonian rocks; 4. The *Age of Acrogens*, or the *Age of Amphibians*, represented by the Carboniferous rocks; 5. The *Age of Reptiles*, represented by the Mesozoic rocks; 6. The *Age of Mammals*, by the Cenozoic; and, 7. The *Age of Man*, by the recent rocks.

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* Ancient animal life. † Old life. ‡ Middle life. # Recent life.

‖ For a full discussion of the subject see Bull. Geol. Dept. of Univ. of Cal., No. 11.

In the accompanying diagram (Fig. 258), vertical height represents the whole course of time, the strong horizontal lines divide this into eras, while the lighter lines, where necessary, separate the ages. The shaded spaces represent the origin, the increase and decrease, in the course of time, of the great dominant classes of animals and plants. To illustrate: The class of reptiles commenced in the uppermost Carboniferous increased to a maximum in the Secondary, or Mesozoic, and again decreased to the present time. It will be seen that the ages correspond with the eras, except in the case of the Palæozoic era. This long and diversified era is clearly divisible into three ages.

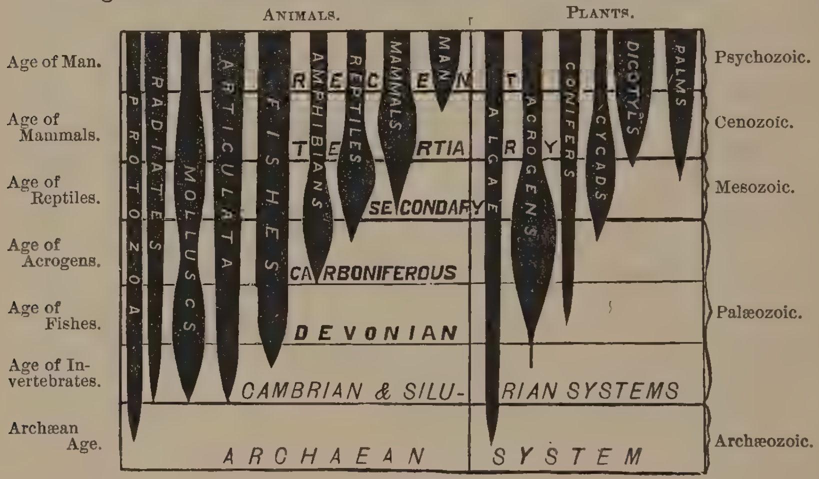

FIG. 258.

Subdivisions.—The subdivisions of eras and ages into *periods* and *epochs* are founded, as already explained (p. 208), on less general unconformity in the rock-system, and less conspicuous changes in the life-system. The names of periods are often, and of epochs are nearly always, local, and therefore different in different countries. We will, of course, use those appropriate to American geology. The table on page 209 represents, as far as periods, the classification used in this country. We have added epochs only in the uppermost part, viz., in the Tertiary and Quaternary.

We give, also (Fig. 259), an ideal diagram of the principal groups of strata which we shall notice, in the order of their superposition, with some examples of characteristic fossils, indicating also the principal places of general unconformity.

The terms used for the divisions of time, and corresponding divisions of rocks, are shown in the accompanying schedule:

Time.	Rocks.
Eras } Ages } . .	Systems.
Periods . .	Series.
Epochs . .	Groups.

Order of Discussion.—Many geologists take up the several epochs and periods of the history of the earth in the inverse order of their occurrence. Commencing with a thorough discussion of "*causes now in operation*," i. e., geological history of the present time, as that which is best known, they make this the basis for the study of the epoch immediately preceding, and which, therefore, is most like it. Having acquired a knowledge of this, the student passes to the preceding, and so on. This has the great advantage of passing ever from the better known to the less known, which is the order of induction. Other geologists prefer to follow the natural order of events. This has the great advantage of bringing out the philosophy of the history—the law of evolution. The first method is the best method of *investigation*; the second method is the best method of *presentation*.

As in human history, so in the geological history, the recorded events of the earliest times are very few and meager, but become more and more numerous and interesting as we approach the present

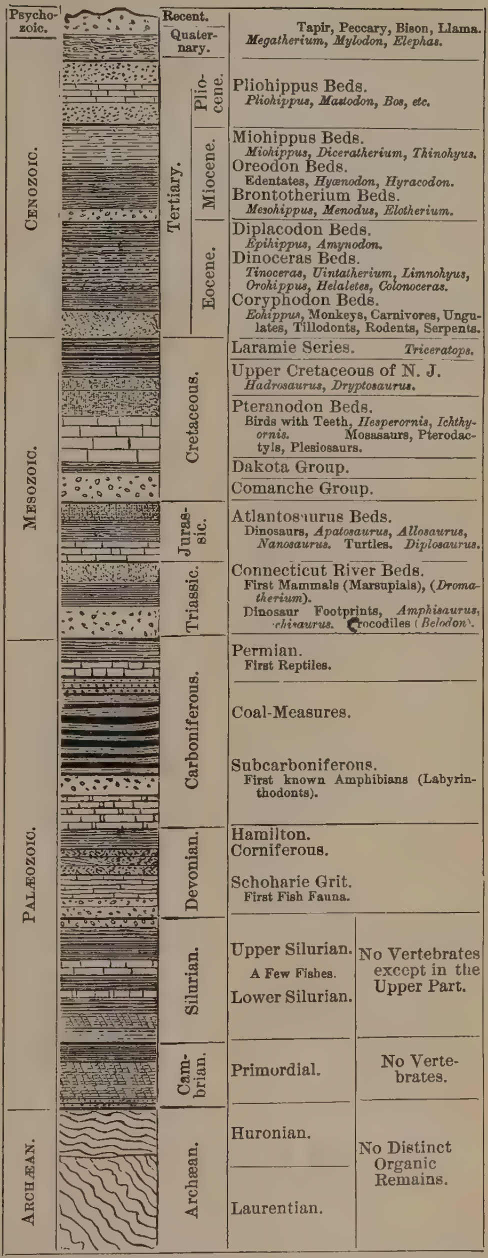
Psychozoic.
Recent.
Quaternary.
Tapir, Peccary, Bison, Llama.
Megatherium, Mylodon, Elephas.
Cenozoic.
Tertiary.
Pliocene.
Pliohippus Beds.
Pliohippus, Mastodon, Bos, etc.
Miocene.
Miohippus Beds.
Miohippus, Diceratherium, Thinohyus.
Oreodon Beds.
Edentates, *Hyænodon, Hyracodon.*
Brontotherium Beds.
Mesohippus, Menodus, Elotherium.
Eocene.
Diplacodon Beds.
Epihippus, Amynodon.
Dinoceras Beds.
Tinoceras, Uintatherium, Limnohyus, Orohippus, Helaletes, Colonoceras.
Coryphodon Beds.
Eohippus, Monkeys, Carnivores, Ungulates, Tillodonts, Rodents, Serpents.
Mesozoic.
Cretaceous.
Laramie Series. *Triceratops.*
Upper Cretaceous of N. J.
Hadrosaurus, Dryptosaurus.
Pteranodon Beds.
Birds with Teeth, *Hesperornis, Ichthyornis.* Mosasaurs, Pterodactyls, Plesiosaurs.
Dakota Group.
Comanche Group.
Jurassic.
Atlantosaurus Beds.
Dinosaurs, *Apatosaurus, Allosaurus, Nanosaurus.* Turtles. *Diplosaurus.*
Triassic.
Connecticut River Beds.
First Mammals (Marsupials), (*Dromatherium*).
Dinosaur Footprints, *Amphisaurus, chisaurus.* Crocodiles (*Belodon*).
Palæozoic.
Carboniferous.
Permian.
First Reptiles.
Coal-Measures.
Subcarboniferous.
First known Amphibians (Labyrinthodonts).
Devonian.
Hamilton.
Corniferous.
Schoharie Grit.
First Fish Fauna.
Silurian.
Upper Silurian.
A Few Fishes.
Lower Silurian.
No Vertebrates except in the Upper Part.
Cambrian.
Primordial.
No Vertebrates.
Archæan.
Huronian.
Laurentian.
No Distinct Organic Remains.

Fig. 255.—Section of the Earth's Crust, to illustrate Vertebrate Life in America. (Slightly modified from Marsh.)

time. Our account of the Archæan era will, therefore, be quite general, and will not enter into any subdivisions, although this era was very long. In the next era we will go into the description of the several ages, in the next into the periods, and in the next even into the *epochs*.

Prehistoric Eras.—Previous to even the dimmest and most imperfect records of the history of the earth there is, as already said (p. 289), an infinite abyss of the unrecorded. This, however, hardly belongs strictly to geology, but rather to cosmic philosophy. We approach it not by *written* records, but by means of more or less probable general scientific reasoning. We pass on, therefore, without pause to the lowest system of rocks containing the record of the earliest era.

CHAPTER II.

ARCHÆAN SYSTEM OF ROCKS AND ARCHÆAN ERA.

It is one of the chief glories of American geology to have established this as a distinct system of rocks and a distinct era.

It had long been known that beneath the lowest Palæozoic rocks there still existed strata of unknown thickness, highly metamorphic and apparently destitute of fossils. These had been usually regarded as lowermost Palæozoic—as the earliest defaced leaves of the Palæozoic volume. But the study of the Canadian rocks, by Sir William Logan, revealed the existence of an enormous thickness of highly-contorted, metamorphic strata, *everywhere unconformable with the overlying Primordial* or Cambrian. More recent observations show this relation not only in Canada, but also in New York, on Lake Superior, in Nebraska, Dakota, Montana, Idaho, Wyoming, Colorado, Utah, Nevada, Texas, New Mexico, and Arizona. Nor is it confined to our own country, for the same unconformable relation has been found by Murchison on the west coast of Scotland, between the lowest Cambrian and an underlying gneiss, evidently corresponding to the Laurentian of Canada. Similar rocks, and in similar unconformable relation, have been found underlying the primordial in Bohemia, and also in Sweden and Bavaria, and many other places. Such general unconformity shows great and wide-spread changes of physical geography at this time, and therefore marks a primary division of time. There seems no longer any doubt, therefore, that it should be regarded as a distinct system.*

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* Van Hise and others of the United States Geological Survey call *Archæan* only the granite and gneiss complex at the base, containing no quartzite, nor limestone, nor iron

The following figures (260, 261, 262) give the relation between the Palæozoic and the Archæan in New Mexico, in Canada, and in Scotland.

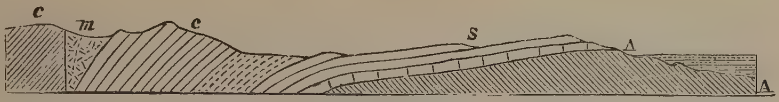

FIG. 260.—Section across Santarita Mountain, New Mexico: *c*, Carboniferous; *S*, Silurian; *A*, Archæan; *m*, metalliferous vein (after Gilbert).

These, then, are the *oldest known* rocks. They form the first volume of the recorded history of the earth. Yet they evidently are not the absolute oldest; evidently they do not constitute any part of the *primitive* crust. For they are themselves *stratified* or *fragmental* rocks, and therefore formed from the *débris* of other rocks still older than themselves; and these last possibly from still older rocks. Thus, we search in vain for the so-called *primary* rocks of the original crust.

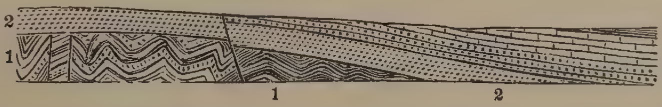

FIG. 261.—Section showing Primordial unconformable on the Archæan: 1, Archæan or Laurentian; 2, Primordial or Lowest Silurian (after Logan).

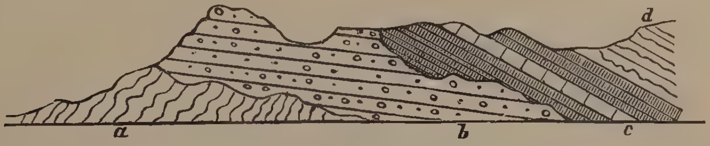

FIG. 262.—Diagram Section, showing the Structure of the North Highlands: *a*, Archæan Gneiss; *b*, Pre-Cambrian; *c*, Cambrian; *d*, Silurian (Jukes).

Thus is it with all history. No *history is able to write its own beginning.*

Rocks.—There is nothing very characteristic in the rocks of the Archæan system, except their extreme and universal metamorphism. They do not differ very conspicuously from metamorphic rocks of other periods; consisting probably of altered sandstones, limestones, and clays. They are all, however, very much contorted and very highly metamorphic. In Canada they consist mainly of the *schist series*,

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ore, nor certain evidences of any kind of sedimentary origin. This they regard as a primitive crust. All other pre-Cambrian rocks they call Algonkian. In the upper parts of these are found some fossils. They call the age, therefore, *Proterozoic*. In this work all pre-Cambrian rocks are called Archæan. The age may well be called Archæozoic, after Dana.

passing on the one hand into gneiss, and on the other into hornblendic gneiss; of sandstones, passing into quartzites; and of *limestones*, passing into marbles. These together, in Canada, form a series of rocks at least 50,000 feet thick.

Interstratified with these are found immense beds of *iron-ore* 100 or more feet thick, and great quantities of *graphite*, sometimes impregnating the rocks, and sometimes in pure seams. In rocks of this age occur the great iron-beds of Missouri, of New Jersey, of Lake Superior, and of Sweden; and probably the mountains of iron recently found in Utah.* The quantity of iron found in these strata is far greater than in any other. It may well be called the Age of Iron.

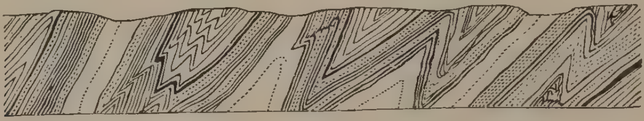
FIG. 263.—Contortion of Laurentian Strata (after Logan).

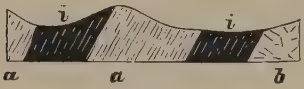

FIG. 264.

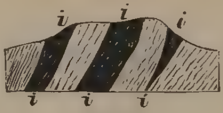

FIG. 265.

The above figures show the contortion of the strata (Fig. 263), and the mode of occurrence of the iron (Figs. 264, 265).

Area in North America.—1. These strata cover the greater portion of Labrador and Canada, and then, turning northwestward, extend to an unknown distance, but probably to the Arctic Ocean. The area forms a broad V, within the arms of which is inclosed Hudson's Bay. It may be seen on maps, pp. 302 and 303. This is the most extensive area known on the continent. 2. On the eastern slopes of the Appalachian chain undoubted patches are found as far south as Virginia, and a larger area in this region is referred with much probability to the same. This is shown on map, p. 302. Its further extension southward along the chain is still doubtful, though probable. 3. In the Rocky Mountain region extensive lines and areas of outcrop are known, trending in the general direction of the chain, and forming the axis of the great ranges. 4. Several small patches are also found scattered about in the basin of the Mississippi, apparently exposed by erosion.

Doubtless the Archæan rocks are far more extended, but covered and concealed by other and later rocks. The area mentioned is the area of surface-exposure. It represents so much of Archæan sea-bottom as was subsequently raised into land, and not afterward again covered by sediments; or, if so covered, again exposed by erosion.

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* Newberry, Genesis of Iron-Ores, School of Mines Quarterly, 1880.

Physical Geography of Archæan Times.—As these are stratified rocks, they must have been formed from the *débris* of still older rocks forming the land of that time. But as they are the oldest known rocks, we know nothing of the position of the land from which they were formed. But since, during the rest of the geological history, the continent has developed from the north toward the south, it seems most probable that this earliest land lay still farther north, perhaps in the North Atlantic region, and disappeared when the Archæan area was elevated into land.

Time represented.—The enormous thickness of these rocks (50,000 feet in Canada, and still greater in Bohemia and Bavaria) certainly indicates a very great lapse of time. It is probable that the Archæan era is longer than all the rest of the recorded history of the earth put together; and yet, precisely as in the beginnings of human history, the record is almost a blank. The events are few, and imperfectly recorded.

Evidences of Life.—We have already explained (p. 150) how iron-ore is at present accumulated. We have there shown that all accumulations of this kind now going on are formed by the agency of organic matter. It is almost certain that the same is true for all times, and therefore that iron-ore accumulations are the *sign* of the existence of organic matter, and the quantity of the ore accumulated is a *measure* of the amount of organic matter consumed in doing the work. The immense beds of iron-ore found in the Archæan rocks are, therefore, evidence of the existence of organisms in great abundance. That these organisms were *chiefly vegetable*, we have the further evidence derived from the great beds of graphite; for graphite, as we shall see hereafter, is only the extreme term of the metamorphism of coal.

Of the existence of *animal* organisms the evidence is not yet complete, although it is probable that the lowest forms of Protozoa, such as rhizopods, were abundant. We have seen that *limestones* are abundant among the Archæan rocks. Now, the limestones of subsequent geological epochs are almost wholly composed of the accumulated shelly remains of lower organisms, especially nullipores and coccoliths among plants, and rhizopods among animals.

The existence of rhizopods is believed by some to have been demonstrated. There have been found abundantly, in the Laurentian limestones of Canada, of Bohemia, of Bavaria, and elsewhere, large, irregular, cellular masses, which are believed by good authorities to be the remains of a gigantic foraminiferous rhizopod. The supposed species has been called *Eozoön** *Canadense.* Fig. 266 is a section of an Eozoönal mass, natural size, in which the white is calcareous matter supposed to have been secreted by the rhizopod, and the dark corresponds to the supposed animal matter of the rhizopod itself.

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* Dawn animal.

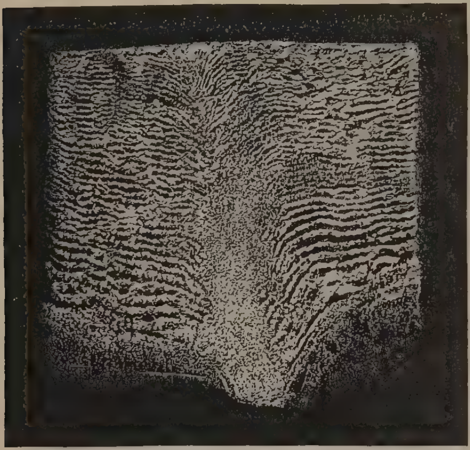

Fig. 266.—Section of the Base of Specimen of Eozoön, × ⅔. From a photograph. (After Prestwich.)

There has been, and is still, much discussion as to the organic or mineral nature of these curious structures. If these irregular masses be indeed of animal origin, it is evident that they belong to the lowest forms of compound protozoa — lower far than the symmetrically-formed foraminifera of later times. It is precisely in such almost amorphous masses of protoplasmic matter that, according to the evolution hypothesis, the animal kingdom might be expected to originate. But their organic origin is not now generally admitted.

Some very obscure tracings, suggesting the *possible* existence of *marine worms*, have been found both in Canada and in Bohemia; but as yet we have no reliable evidence of any animals higher than the *protozoa*. It is impossible to say that other animals of low form did not exist; yet the absence of any reliable trace in rocks not more metamorphic than some of the next era, which are crowded with fossils of many kinds, seems to indicate a paucity, if not an entire absence, at this time, of such animals. Recently radiolarians, foraminifera, and sponges have been found in Brittany in rocks of supposed pre-Cambrian age* Also Walcott finds in the Grand Cañon walls below the lowest Cambrian (Olenellus zone) remains of even brachiopods and trilobites.† But the pre-Cambrian age of these rocks is perhaps doubtful.

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* Geol. Mag., vol. i, p. 417, 1894; Am. Nat., vol. xxx, p. 53, 1896.

† Bull. U. S. Geol. Soc., No. 86, pp. 469–492, 1892.

CHAPTER III.

PALÆOZOIC SYSTEM OF ROCKS AND PALÆOZOIC ERA.

General Description.

THIS is a distinct system of rocks, revealing a distinct *time-world*—a distinct *rock-system*, containing the record of a distinct *life-system.* The *rock-system* is distinct, being everywhere *unconformed to the Archæan below and the Mesozoic above*—a bound volume—volume second of the Book of Time. The *life-system* is also equally distinct, being conspicuously different from that which precedes and that which follows. Whatever of life existed before, its record is too imperfect to give us a clear conception of its character. But in the Palæozoic the evidences of abundant and very varied life are clear; more than 20,000 *species having been described.* It stands out the most distinct era in the whole history of the earth. The Archæan must be regarded as the *mythical period.* Here, with the Palæozoic, commences the true dawn of history.

Rocks—Thickness, etc.—The rocks of this system, although less powerful than the preceding, are also of enormous thickness compared with those of later geological times, being in the Appalachian region about 40,000 feet; in Nevada, about 40,000 feet; in the Wahsatch Mountains, 33,000 feet (King). But these extreme thicknesses are more local than in the case of the Archæan. It is believed that we are safe in saying that the time represented by them is equal to all subsequent time to the present.

There is nothing very characteristic in the rocks composing Palæozoic strata, though the practiced eye may often distinguish them by their lithological character. Though strongly folded and highly metamorphic in some regions, these characters are not so universal as in the Archæan.

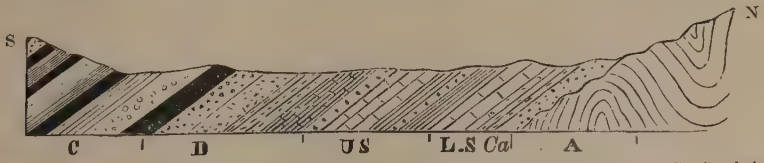

FIG. 267.—Ideal Section north and south from Canada to Pennsylvania: *A*, Archæan; *Ca*, Cambrian; *L S* and *U S*, Silurian; *D*, Devonian; *C*, Carboniferous.

In the United States the rocks of the whole system are often conformable—for example, in New York and in Utah. In Europe, on the contrary, the principal divisions are usually unconformable. In this country, therefore, the subdivisions are founded almost wholly on change in the life-system; while in Europe the same subdivisions are founded on unconformity of the rock-system, as well as change in the life-system. Further, in this country, in passing from Pennsylvania, through New York, into Canada, we pass over the outcropping edges of the whole system, from the highest to the lowest, and finally on to

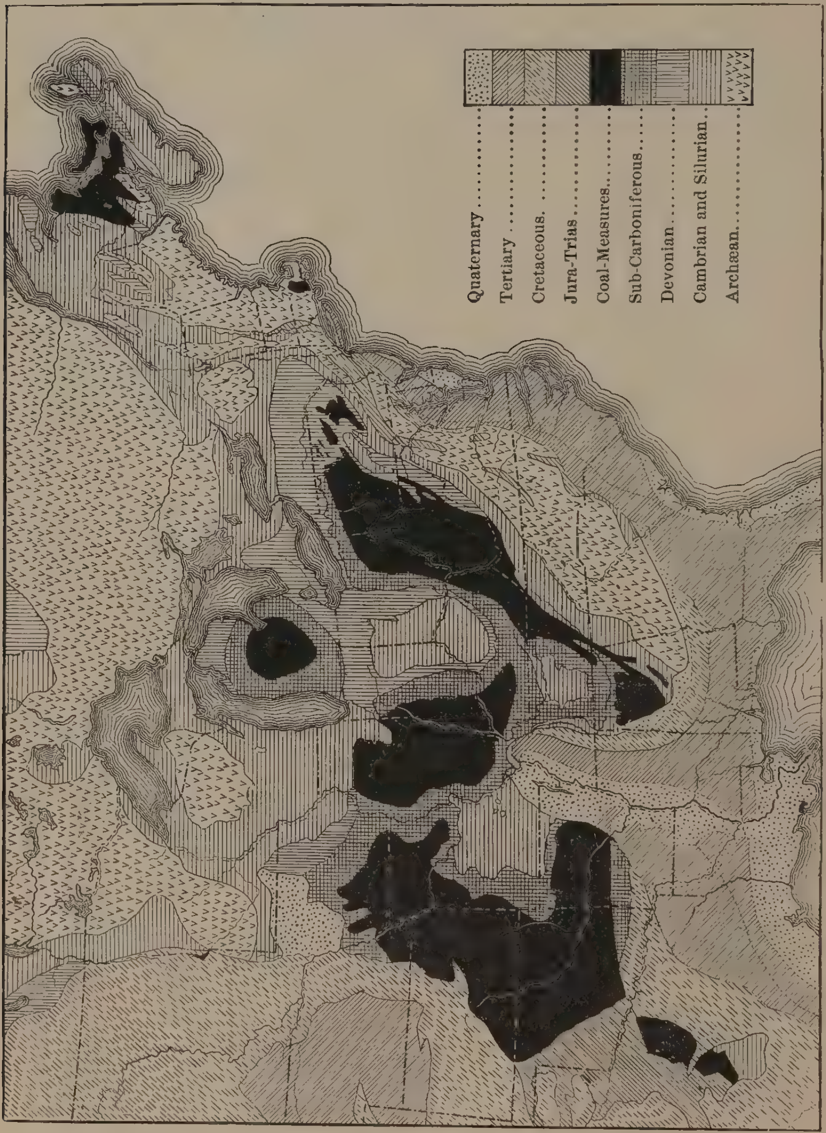

Fig. 268.—Geological Map of the Eastern Part of the United States.

the Archæan (Fig. 267). This, taken in connection with the conformity of the rocks, shows that during the Palæozoic the continent in this part was successively developed, from the north toward the south, by bodily upheaval of the Archæan area and successive exposure of contiguous sea-bottom. In Europe the oscillations seem to have been more frequent and violent.

Fig. 267 is a section from Pennsylvania to Canada, showing the relation of the subdivisions to each other, and the manner in which they lie on the Archæan. This will be better understood if the map (Fig. 271) on page 309 be at the same time carefully examined.

Area in the United States.—The area in the Eastern United States in which the country rock belongs to this system is seen in the map above (Fig. 268). It may be stated roughly to embrace all that part included between the Great Lakes on the north, the Blue Ridge of the Appalachian chain on the east, the Prairies on the west, and Middle Alabama and Southern Arkansas on the south. It includes the richest portion of our country. Besides this great continuous area there are also areas of imperfectly known size and shape in the Rocky Mountain region, and on either side of the Sierra Nevada.

Physical Geography of the American Continent.—At the beginning of the Palæozoic era (Primordial) the land was substantially the *Archæan area*, already described, *plus* certain areas of Archæan rocks which were then land, but have been *subsequently covered* by later deposits

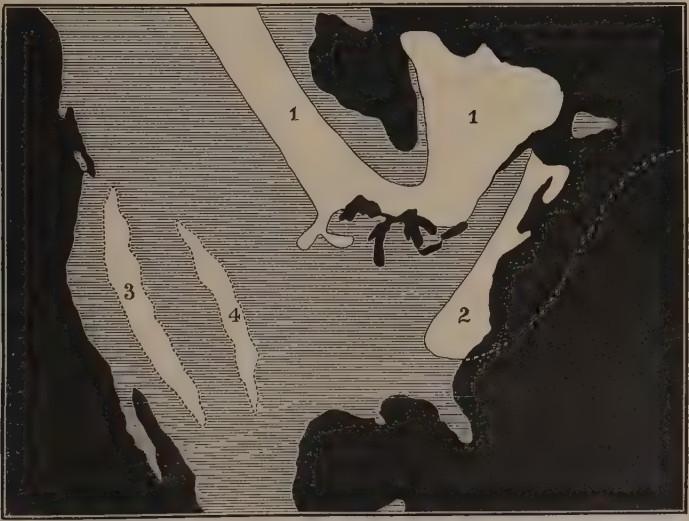

FIG. 269.—Map of Primordial Times: Black, existing seas and lakes; light shade, portions of the continent then covered by sea; white areas, then land; when limits doubtful, surrounded by dotted line. In case of area 2 the land extended beyond the present shore-line to an unknown distance, represented by the white dotted line.

—*minus* certain Archæan areas which have been *subsequently exposed* by erosion. The map (Fig. 269) * is an attempt to represent approximately the continent of that time. It consisted (1) of a great *Northern* land-mass corresponding roughly to the Canadian V-shaped Archæan area. (2) An *Eastern* land-mass, including the Appalachian Archæan area, but extending far beyond it to the eastward (for the coast strata here are Cretaceous and Tertiary, resting directly on Archæan, without any Palæozoic between), and probably beyond the present limits of the continent. This is shown by the white dotted line. It possibly connected in North Atlantic region with mass No. 1. (3) A large Western land-mass of unknown shape and size in the Basin region. (4) A large land-mass in the region of the Colorado and Park ranges. There are still other small Archæan areas, but these were probably not land at that time, but have been exposed by erosion. Between these land-masses on the north, the east, and the west, there was an immense sea —*the great interior Palæozoic Sea.*

The reason for thinking that the Eastern land-mass was an extensive one is the immense thickness of Palæozoic sediments which accumulated in the sea along its western border. The reason for thinking that there was a large strip of land in the Basin region is, because in a large part of that region the Mesozoic rocks rest directly and unconformably on Archæan, the *whole Palæozoic being wanting.*

This was the continent at the *beginning* of the Palæozoic era. From this as a nucleus the continent somewhat steadily developed until the whole of the Palæozoic area was added to it, and the continent became perhaps somewhat like that represented on page 486, as the continent of Cretaceous times. In this development the Canadian shore-line advanced steadily southward, but the shore-line of the eastern land mass was almost stationary. This accounts for the great thickness of sediments along that line.

If we compare the Palæozoic rocks of the Appalachian region with the same in the central portion of the Mississippi basin, we observe the following changes as we go westward : (*a*) The rocks in the Appalachian region are highly *metamorphic ;* as we go westward, they become less and less so, until in the region about the Mississippi River they are wholly *unchanged.* (*b*) In the Appalachian region they are strongly and complexly *folded ;* as we go west, these folds pass into gentle undulations, which die away into *horizontality* (see section, Fig. 229, on p. 263). (*c*) In the Appalachian region they are about 40,000 feet thick ; as we go west, they thin out until the whole series is only

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* A map similar to the above, but containing also small scattered patches of Archæan exposures, is sometimes spoken of as an *Archæan* map of North America, or map of Archæan land. It must be borne in mind, however, that it represents indeed land of Archæan *strata*, but, for that very reason, not of Archæan *time*, but of Primordial time.

4,000 feet at the Mississippi. (*d*) In the Appalachian region *grits and sandstones and shales* predominate greatly over limestones; as we go west, the proportion of *limestones* increases, until these are the *predominating rocks.* These four changes are closely connected with each other, and all with the formation of the Appalachian chain, as we have already explained in the chapter on Mountain-Formation (p. 269).

Subdivisions.—The Palæozoic era is divided into three *ages*, which are embodied in three subordinate rock-systems. These ages are each characterized by the dominance of a great class of organisms. They are: 1. The *Age of Invertebrates*, or sometimes called *Age of Mollusks*, in the Lower Palæozoic system, including the Cambrian and Silurian; 2. The *Age of Fishes*, in the Devonian system; and, 3. The *Age of Acrogens and Amphibians*, in the Carboniferous system. These are three chapters in the Palæozoic volume.

These three systems are generally conformable with each other in the Palæozoics of the United States, as we have already shown, but elsewhere they are often unconformable. Before taking up the first in the order of time, viz., the Age of Invertebrates, it is necessary to say something of the *interval* which in our record separates the Archæan from the Palæozoic era.

The Interval.

We have already seen that the lowest Cambrian lies unconformably on the upturned and eroded edges of the crumpled strata of the Archæan. We have also shown (page 187) that unconformability indicates always an oscillation of the earth's crust at the observed place. More definitely it indicates an upheaval, by which the lower series of rocks became land-surface, and were at the same time, perhaps, crumpled; then a long period *unrecorded* at that place, during which the land was eroded and the edges of the crumpled rocks were exposed; then a subsidence, and the deposit of the upper series of rocks on these exposed edges. Now, oscillation necessitates increase and decrease of land-surface. Evidently, therefore, such increase and decrease of land-surface took place in the unrecorded interval between the Archæan and Palæozoic eras; and the length of this unrecorded interval is measured by the amount of erosion which the Archæan underlying the lowest Palæozoic has suffered. We have stated that the land at the beginning of the Palæozoic era was approximately the Archæan area. The shore-line of the earliest Palæozoic sea was the line of junction between the *Cambrian* and *Archæan* (see maps, Figs. 268 and 271). *But this was not the shore-line at the end of the Archæan* time. Evidently this shore-line was much farther south; evidently the land-area was much greater at the end of the Archæan than at the beginning of the Palæozoic. The Archæan era was closed by the *upheaval* into land-surface and the crumpling of the strata of the whole Archæan area, and *much more*. Then followed an interval of which we know nothing, except that it was of long duration, during which the crumpled Archæan strata forming the then land-surface were *deeply eroded*. Then, at the end of this interval came a *subsidence* down to the shore-line already indicated as the Primordial shore-line, and the Palæozoic era commenced, its first sediments being of course deposited on the exposed edges of the submerged Archæan rocks.

I have attempted to illustrate these facts by the following diagrams (Fig. 270), in which the last, *e*, represents a north and south section of

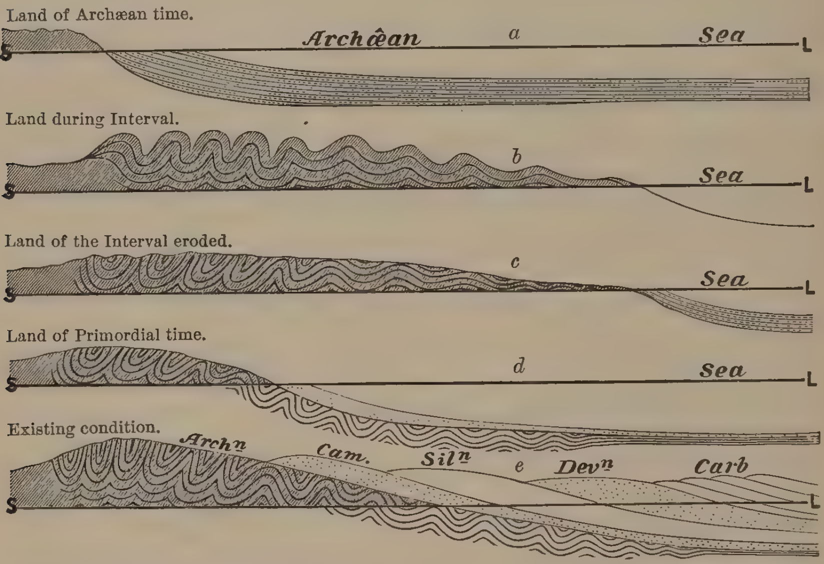

FIG. 270.—Ideal Section, showing how Unconformity was produced on the Canadian Border: *S L*, sea-level.

the Archæan and Palæozoics of the Canadian border, and southward to Pennsylvania. The crumpled and eroded strata of the Archæan are seen to underlie unconformably the primordial rocks for some distance south—how far we know not. This is the present condition of things. How it came about is shown in *a*, *b*, *c*, and *d*. In *a*, we have the supposed condition of things in Archæan times. The position of the land was somewhere northward—we know not where. In *b*, a large portion of Archæan marginal sea-bottom was raised into land, and at the same time crumpled. In *c*, the same was eroded, so that the edges of strata were exposed. This was during the *interval*. In *d*, the land sank again to the *primordial* shore-line, and the Palæozoic era commenced. During the Palæozoic the land gradually rose so as to expose successive sea-bottoms of Cambrian, Silurian, Devonian, and Carboniferous ages. It has remained substantially in this condition ever since.

We have spoken thus far only of the unconformity of the New York rocks on the Canadian rocks. This phenomenon may be explained, as we have seen, by local oscillations, with increase and decrease of land-area during the lost interval. But, when we remember that the same unconformity is found in the most widely-separated localities, over the whole area of the United States; that the Grand Cañon of the Colorado cuts through the Cambrian into the Archæan and we find the same unconformity; that artesian wells in all parts of the Palæozoic basin reach the Archæan and find it unconformable—we are forced to the conclusion that the lost interval, as compared with the Primordial, was probably a *continental* period—a period of widely-extended land composed of Archæan rocks. The whole of this land disappeared by submergence at the beginning of the Primordial, except the Canadian area, a large area east of the Appalachian, probably a considerable area in the Basin region, another in the Colorado mountain region, and perhaps a few islands or larger areas in the Primordial seas between, as shown in map, Fig. 269. In a word, the Interval was a *Continental* period between two *Oceanic* periods.

In all speculations on the origin of the animal kingdom by evolution, it is very necessary to bear in mind this *lost interval*, for it was evidently of great duration.

We have spoken of the Interval as *one.* But their may have been several. Our knowledge of the pre-Cambrian rocks is too imperfect to allow us to speak confidently.

SECTION 1.—LOWER PALÆOZOIC SYSTEM (INCLUDING CAMBRIAN AND SILURIAN): AGE OF INVERTEBRATES.

The Rock-System.—The rocks of this age have been carefully studied in England, by Sedgwick and Murchison; in Russia and Sweden, by Murchison; in Bohemia, by Barrande; and in New York, by Hall. The divisions and subdivisions established by these geologists have become the standard of comparison elsewhere. The system was first clearly defined by Murchison in Wales. The name Silurian was given by Murchison to the rocks of the *whole age.* The name *Cambrian* was given by Sedgwick to the lower part. The great thickness and exceptional importance of this lower part have induced most geologists to erect this into a distinct system equivalent to the Silurian, and to call it *Cambrian*, or *Primordial.* From the point of view of the progress of life, however, they may be united as one *Age.*

Subdivisions.—The following table gives the divisions and subdivisions of the rocks and the corresponding *periods* of the age in this country:

Lower Palæozoic Age or Age of Invertebrates. .	Upper Silurian.	Lower Helderberg Period.
		Salina “
		Niagara “
	Lower Silurian.	Trenton “
		Canadian “
	Cambrian or Primordial.	Dikellocephalus “
		Paradoxides “
		Olenellus “

The larger divisions, viz., Cambrian, Lower Silurian (or Ordovician), and Upper Silurian, are generally recognized. The subdivisions are largely local, each country having its own; but they are synchronized, as far as possible, by comparison of fossils.

Character of the Rocks.—The rocks of this age, like nearly all rocks, are greatly disturbed and metamorphosed in mountain-regions, though less so than the Archæan; but in Sweden and Russia, and in the valley of the Mississippi, they are found in their original horizontal position, and not greatly changed from their original sedimentary condition.

Area in America.—By turning to the map (Fig. 268) it will be seen: 1. That the Lower Palæozoic is attached to the Canadian Archæan nucleus as an irregular border on the outer side of the V-shaped area; 2. Again, the Appalachian Archæan region is also bordered on the west side by a narrow strip of the same; 3. Also we observe large patches in the interior—one about Cincinnati, another occupying the southern portion of Missouri and northeastern portion of Arkansas, and one in Middle Tennessee; 4. Also narrow bands on the flanks of nearly all the Rocky Mountain ranges; 5. Also considerable areas in the Basin region, the outlines of which are little known; 6. Recently areas have also been found in Northern California (Diller).

Physical Geography.—At the beginning of this age, as already said, the land was approximately the Archæan area (Fig. 269). The Lower Palæozoic, which embraces the great V-shaped Archæan area on the southeast, south, and southwest, was then the sea-bottom border of the coast of the Primordial continent. The same rocks bordering the Appalachian Archæan was also then a sea-bottom bordering the Primordial continent in that region. It is probable, also, that these rocks in the Rocky Mountain region also border Archæan areas, and these areas represent Primordial continents, and the Cambrian border the marginal sea-bottom of that time. The other patches mentioned in the interior were probably bottoms of open seas.

Now, the Cambrian and Silurian areas represent so much of sea-bottoms as were raised into land-surfaces during or at the end of that time, and not subsequently covered by sea.* Therefore, at the beginning of that time the land was the Archæan area; while at the end the land was increased by the addition of the Lower Palæozoic area. This addition was not all made at once, but very gradually. The steps of this increase have been carefully studied in New York. The map (Fig. 271) shows the principal successive steps, as does also the section (Fig. 267) with which it should be compared. Inspection of these figures shows not only the Cambrian and Silurian bordering the Archæan, but the rocks of the several periods bordering each other successively; so that in walking from Pennsylvania to Canada, or to the Adirondack Mountains of New York, along the line *S N*, we successively walk over the Carboniferous, the Devonian, the Silurian, Cambrian, and the Archæan; and in the Silurian and Cambrian over rocks of the successive periods, from the highest to the lowest. This plainly shows that during this age the continent (Archæan area) was slowly upheaved, and contiguous sea-bottoms successively added to the land, and the shore-line gradually pushed southward from the Canadian region, and probably westward from the land-mass along the Appalachian. Of course, therefore, the *oldest* Cambrian shore-line was the most northern and eastern. This is the *primordial beach*:

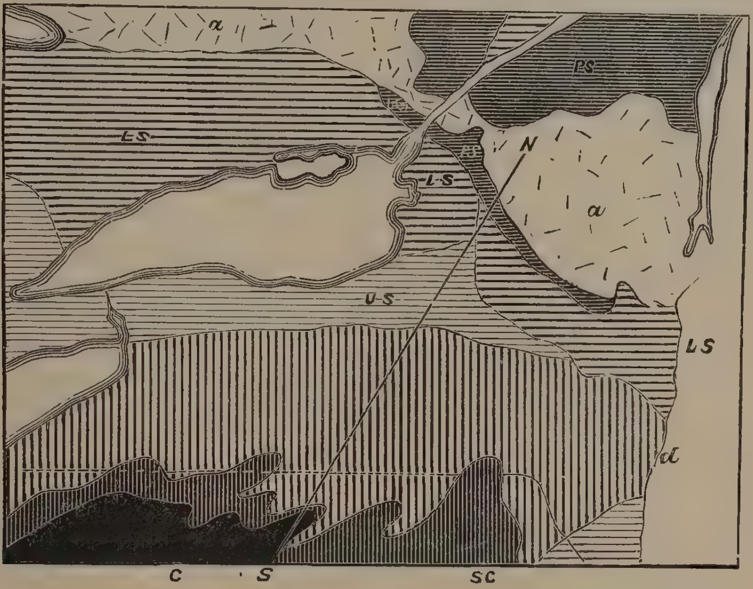

FIG. 271.—Geological Map of New York: *a*, Archæan; *PS*, Primordial; *LS*, Lower Silurian; *US*, Upper Silurian; *d*, Devonian; *SC*, Sub-Carboniferous; *C*, Coal-measures; *NS*, line of section, shown in Fig. 267.

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* This is true as a broad, general fact; but patches of Silurian may also be exposed by *removal* of later deposits by erosion.

CAMBRIAN SYSTEM.

Primordial Beach and its Fossils—The First Fauna.

As already stated, the elementary character of this treatise renders it impossible to take up separately the several periods of this age. We must confine ourselves to a general description of the age only. But there is so peculiar and special an interest connected with the dawn of life on the earth, that, before taking up the life-system of the whole age, it seems necessary to say something of the *earliest fauna.*

We have seen that at the beginning of Cambrian times a large V-shaped mass of land occupied the region now embraced by Canada and Labrador, and stretched northwestward to an unknown distance, the two arms of the V being nearly parallel to the two present shores of the American Continent; further, that a land-mass of extent unknown occupied the position of the eastern slope of the Appalachian chain; also, that land of unknown extent occupied the position of the Rocky Mountains and Basin region; and the continent was thus early sketched out. Now, southward of the first-mentioned land-area and between the other two there was a great interior sea, which we have called the *Interior Palæozoic Sea.* The shores of that sea beat upon the continental masses north, east, and west, and accumulated, on exposed places, a *beach.* Patches of that earliest beach still remain. They are found, of course, closely bordering the Archæan rocks, Canadian and Appalachian, and lying unconformably upon them. They are the primordial sandstones and slates of Canada, New York, Pennsylvania, Virginia, and probably Tennessee and Georgia. The fact that these are indeed remnants of a beach is proved by the existence, in almost every part, of *shore-marks* of all kinds—such as ripple-marks, sun-cracks, worm-tracks, worm-borings, broken shells, etc.

This, then, is the *old primordial beach.* It is of the extremest interest to the geologist because it marks the outline of the earliest Cambrian sea, and contains the remains of the earliest Cambrian fauna. Indeed, we may say it contains the remains of the *earliest known fauna.* It is true, the lowest Rhizopods and sponges probably existed in Archæan times, but these can not be said to constitute a fauna. With the very commencement of Cambrian times, however, we find at once a considerable variety of animal forms.

What, then, was the character of this earliest fauna and flora? If we could have walked along that beach when it was washed by primordial seas, what would we have found cast ashore? *We would have found the representatives of all the great types of animals except the vertebrata.* The Protozoa and lowest Metazoa were then represented by *Rhizopods* and *sponges*; the Celenterates by *corals* and *Hydrozoa*

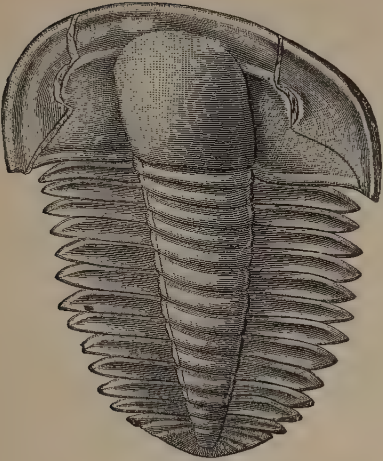

FIG. 272.

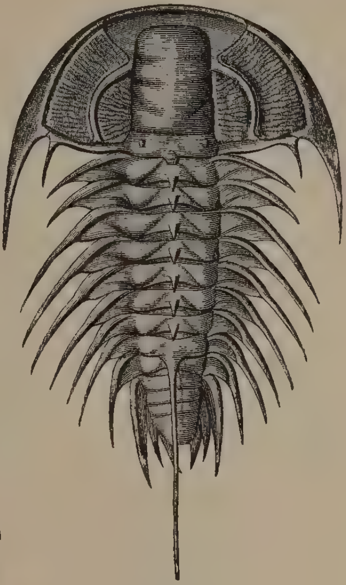

FIG. 273.

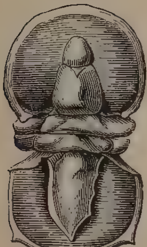

FIG. 274.

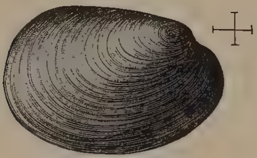

FIG. 275.

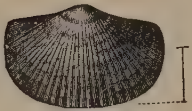

FIG. 276.

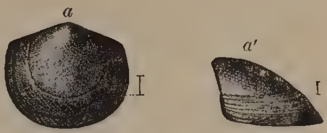

FIG. 277.

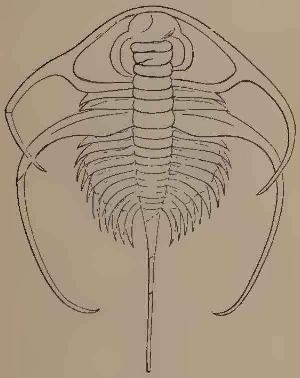

FIG. 278.

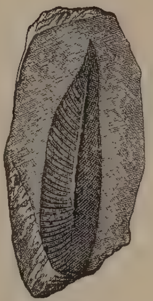

FIG. 279.

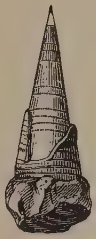

FIG. 280.

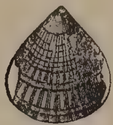

FIG. 281.

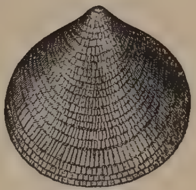

FIG. 282.

FIGS. 272-282.—AMERICAN CAMBRIAN FOSSILS (after Walcott and White): 272. Protypus Hitchcocki, + 2. 273. Zacanthoides typicalis, + 2. 274. Agnostus interstrictus. 275. Fordilla Troyensis. 276. Orthisina transversa. 277. Paterina pannula—*a*, front view; *a′*, side view. 278. Olenellus Gilberti. 279. Diplograptus simplex. 280. Hyolithes primordialis. 381. Lingulella celata. 282. Obolella crassa.

(graptolites); the Echinoderms by Cystidean *Crinoids;* the mollusks by by *Brachiopods* (Figs. 276, 277, 281, 282, 285, 288, 289), *Lamellibranchs* (Figs. 275, 287), *Gasteropods* (Pleurotomaria), *Pteropods* (280, 286), and even *Cephalopods* (orthoceratites); the Arthropods by *Crustacea* (trilobites and phyllocarids, 272, 273, 274, 278, 290, 291); and the worms by *tracks* and *tubes* (Fig. 284). Plants were represented by *Fucoids* (Fig. 283). These widely-distinct classes are already clearly differentiated and somewhat highly organized. Nor is the fauna a meager one in number of species. In the United States and Canada alone about 400 species are already known in the Cambrian, of which nearly 100 are *trilobites;* and in the lowest zone of the Cambrian, viz., *Olenellus beds*, there are 141 species, of which 51 are *trilobites* (Walcott). About a dozen species of plants are also known. When we recollect the great age of these rocks and their usual metamorphism, and the fragmentary character of all fossil faunas, it seems certain that great abundance and variety of life existed already in these early seas. Of this life the trilobites, by their size, their abundance, their variety, and their high organization, must be regarded as the dominant type. Among the largest trilobites known at all are some from this period. The Paradoxides, represented in Figs. 292 and 293, attained a length of twenty inches. English beds of the same age furnish specimens of the same genus nearly two feet long.

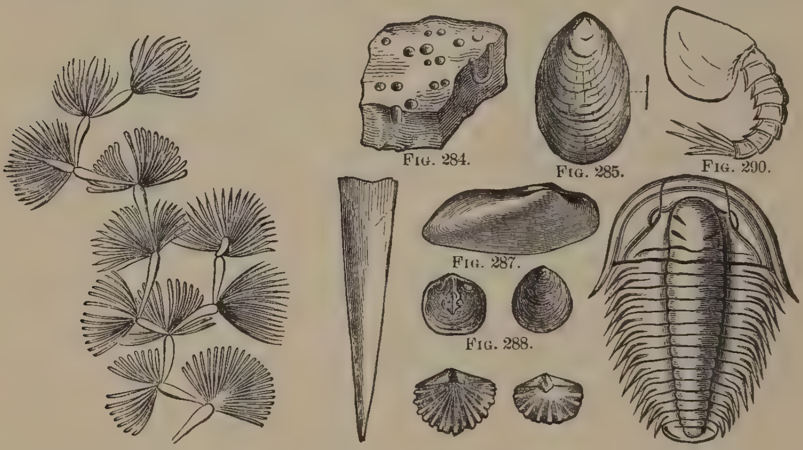

Fig. 284. Fig. 285. Fig. 290. Fig. 287. Fig. 288.

Fig. 283. Fig. 286. Fig. 289. Fig. 291.

Figs. 283–291.—Foreign Primordial Fossils: 283. Oldhamia antiqua, probably a plant. 284. Arenicolites didymus, worm-tubes. 285. Lingulella ferruginea. 286. Theca Davidii. 287. Modiolopsis solvensis. 288. Obolella Hicksii. 289. Orthis sagittalis. 290. Hymenocaris vermicauda. 291. Olenus macrurus.

We give in the above figures a few of the more remarkable primordial forms taken from the rocks of this country, and of foreign countries. They are intended only to give a general idea of the fullness and variety of the primordial life; the affinities of these fossils will be discussed hereafter.

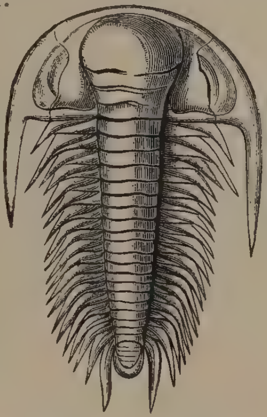

Fig. 292.—Paradoxides Bohemicus, Foreign.

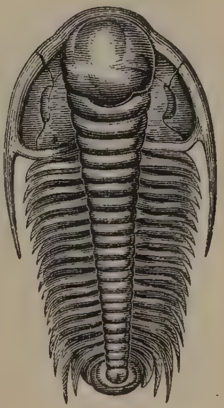

Fig. 293.—Paradoxides Harlani, × $\frac{1}{6}$ (after Rogers), American.

General Remarks on First Distinct Fauna.—There are several points of great philosophic interest suggested by the nature of these first organisms:

1. Plants in this, and in all other geological periods, are far less numerously represented in a fossil state than animals. This can not be because animals were more abundant than plants, for since the animal kingdom subsists on the vegetable kingdom, and since every animal consumes many times its own weight of food, plants must have been always more abundant than animals. The true reason of the greater abundance of animal remains is to be found in the fact that the hard parts of animals are far more indestructible than any portion of vegetable tissue.

2. At the end of the Archæan times—when the Archæan volume closed—we find, if any, only the lowest Protozoan life with possibly sponges. But with the opening of the next era, apparently with the first pages of the next volume, we find already all the great types of structure except the vertebrata. And these are not the lowest of each type, as might have been expected, but already trilobites among Arthropods, and Cephalopods among Mollusca—*animals which can hardly be regarded as lower than the middle of the animal scale.*

We must not hastily conclude, however, that these widely-divergent and highly-organized types originated together at once. We must remember that between the Archæan and Palæozoic there is a *lost interval* of enormous duration. Evidently, therefore, the Primordial fauna is *not the actual first fauna.* Evidently we have not yet recovered the leaves in which is recorded the gradual differentiation of these widely-distinct types. All this must have taken place *during the lost interval.*

But if, on the other hand, we suppose, as many do, that evolution proceeds always "with equal steps," then we are forced to the very improbable conclusion that the lost interval is equal to all geological times which followed to the present; for the differentiation of types which occurred during that interval is equal in value to all that has taken place since.

Therefore, we are compelled to admit that there have been in the history of the earth periods of rapid change in physical geography, and periods of comparative quiet in this respect; that, corresponding with these, there have been also periods of rapid evolution of the organic kingdom, developing new forms, and periods in which forms are more stationary. The periods of rapid change are marked by unconformity, and are therefore unfortunately often lost.*

As we proceed, we will probably find many examples of rapid change which must be accounted for in a similar manner.

Life-System of the Silurian.

There were evidently extraordinary abundance and variety of life in the Silurian. These early seas literally swarmed with living beings. The quantity and variety of life—the number of *individuals* and of *species*—were probably not less than at the present time; though orders, classes, and departments, were less diversified. Over 10,000 species have been described from the Silurian alone (Barrande); and these must be regarded as only a small fragment of the actual fauna of the age. In certain favored localities, the number of species found in a given area of a single stratum will compare favorably with the number now existing in *an equal area* of our present sea-bottoms. Yet, in all this teeming life there is not a single species similar to any found in any other geological time. And not only are the species peculiar, but even the genera, the families, and the orders are different from those now existing.

We can give only a very brief sketch of this early life, touching only the most salient points, especially such as throw light on the great question of evolution.

Plants.

With the exception of a few small land-plants, ferns, and club-mosses, recently found in the Lower Silurian of both this country and Europe,† and of which we shall speak again, the only plants yet found are the lowest forms of cellular cryptogams, viz., *marine algæ* or seaweeds. It is difficult, from the impressions left by these to determine

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* In spite of every allowance the suddenness of the appearance of the first fauna is extraordinary. In this connection, Brooks (Jour. Geol., vol. ii, p. 455, 1894) has thrown out a very suggestive thought. He gives reasons for thinking that the first forms of life were *pelagic*, floating freely in the open sea, of gelatinous consistence, and therefore not preserved. Food was abundant (microscopic plants), struggle for life not severe, and therefore there was little differentiation of forms. About the beginning of the Cambrian there was a *discovery of the bottom*, especially near shore. Now support was necessary, and therefore *hard parts* were formed and thus *they were preserved*. Now also they became *crowded*, struggle and competition became severe, and *differentiation* into main types commenced.

† Lesquereux, American Journal of Science, 1878, vol. xv, p. 149.

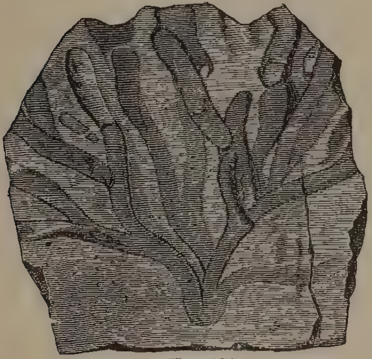


Fig. 294.

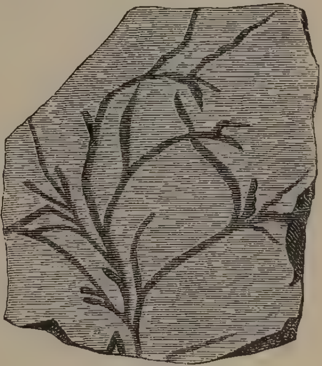


Fig. 295.

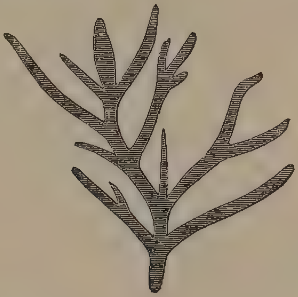


Fig. 296.

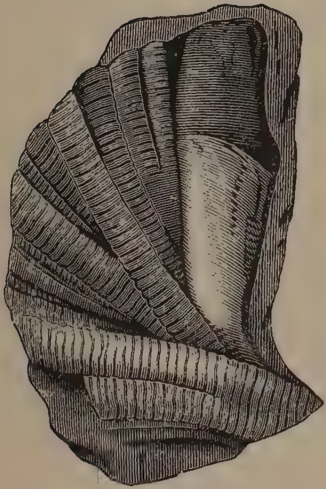


Fig. 297.

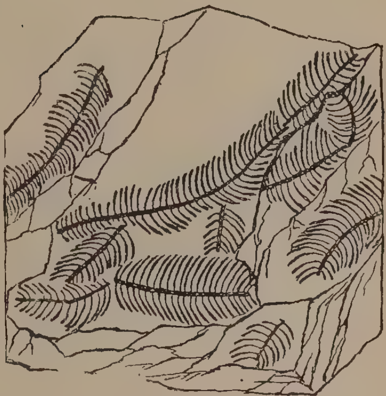


Fig. 298.

Figs. 294–298.—Silurian Plants (after Hall): 249. Buthotrephis succulens. 295 and 296. Buthotreptus gracilis. 297. Arthrophycus Harlani. 298. Buthograptus laxus (after Whitfield).

genera, much more species, with any degree of certainty. We shall, therefore, call them by the general somewhat indefinite name of *Fucoids* (*Fucus*, tangle or kelp), or Fucus-like plants. As already stated, plants are far less abundantly and perfectly preserved than animals, on account of their want of a skeleton. A few characteristic forms are given in Figs. 294–298.

Animals.

Sponges.—The large, *irregular* masses which are called Eozoön seem entirely characteristic of Archæan times. If they are indeed of animal origin, they are replaced in the Lower Palæozoic by more regular forms which are usually called *sponges.* Of these, the most characteristic Silurian genera are Stromatopora and Receptaculitis (Figs. 299–305). They seemed to have formed large coralline masses, which are now regarded either as hydrocorals (Stromatopora) or as sponges (Receptaculites).

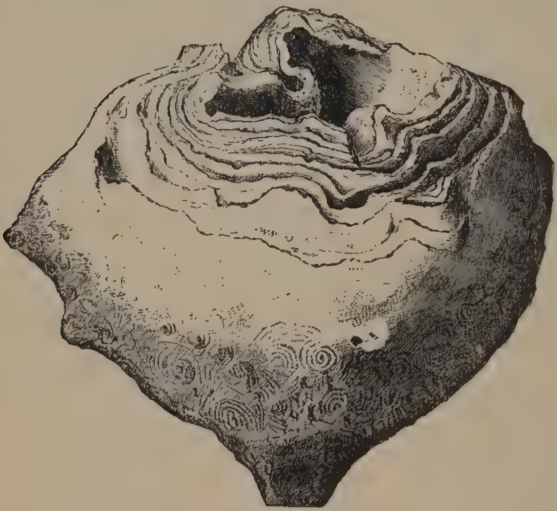


FIG. 299.—Stromatopora rugosa.

Corals.—Corals were very abundant, forming often whole rock-masses, as if they, while living, formed *reefs.* These, if they indicate warm seas, show a great uniformity of temperature, since they are found in all portions of the earth alike.

The corals of this age belong principally to three families, viz., *Cyathophylloids*, or *cup-corals ; Favositidæ*, or *honey-combed corals ;* and *Halysitidæ*, or *chain-corals.* They are remarkable in not usually being profusely and widely branched like most modern corals, but consisting mostly of masses of parallel or nearly parallel columns. In *Cyathophylloids* (Figs. 306–308) the corals are sometimes separate and of a horn-like form, and sometimes aggregated in large, rough, columnar masses (Rugosa). Their upper portions are *cup-shaped*, and the radiating *laminæ* are very distinct. In *Favositids* (Fig. 309) the hexagonal parallel columns are divided somewhat minutely by horizontal plates (Tabulata) (Fig. 309, *a*), giving a cellular structure which may be finer or coarser. The *Halysitids* (Fig. 311) seem to be made up of small, hollow, flattened columns with imperfect septa, united to form reticulating fluted plates, which on section have the appearance of chains

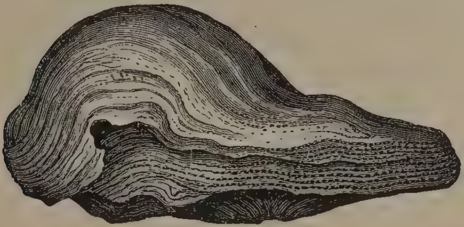


FIG 300.

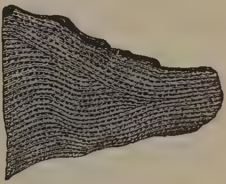


FIG. 301.

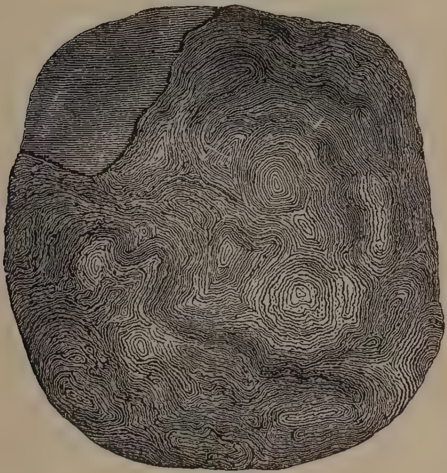


FIG. 302.

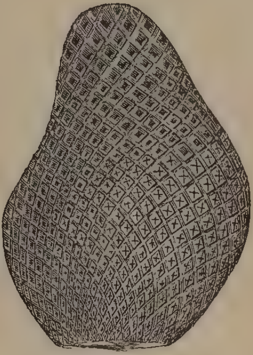
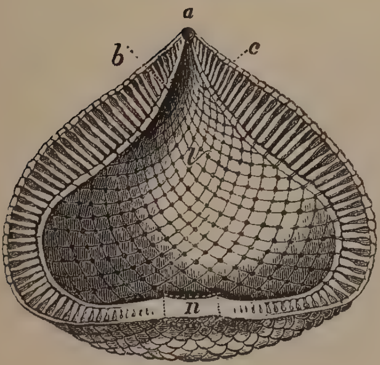


FIG. 303.



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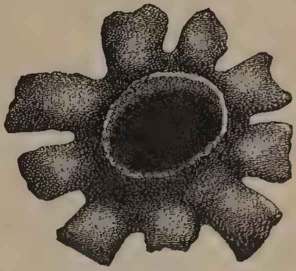
FIG. 305.

FIGS. 300–305.—SILURIAN SPONGES: 300. Stromatopora concentrica. 301. Section of same. 302. View from above (after Hall). 303. Receptaculites formosus (after Worthen). 304. Diagram showing structure of Receptaculites (after Nicholson). 305. Brachiospongia Rœmerana, × ¼ (after Marsh).

crossing in all directions. These are also minutely tabulated. The Syringoporoids (Fig. 310) are similar to the Halysitids, except that the hollow columns are cylindrical and connect with each other only in places.

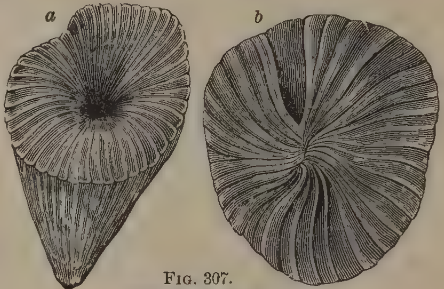

Fig. 307.

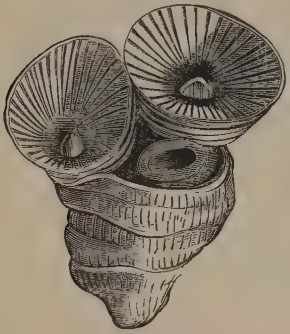

Fig. 306.

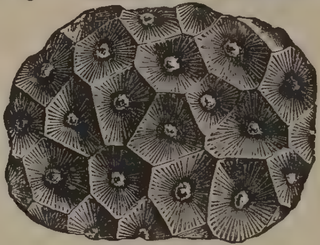

Fig. 308.

Figs. 306–308.—Cyathophylloid Corals: 306. Lonsdaleia floriformis (after Nicholson). 307. *a* and *b*. Zaphrentis bilateralis (after Hall). 308. Strombodes pentagonus (after Hall).

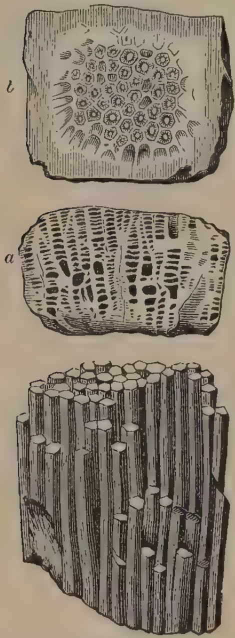

Fig. 309.

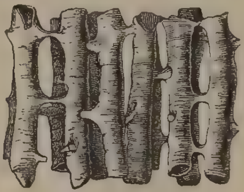

Fig. 310.

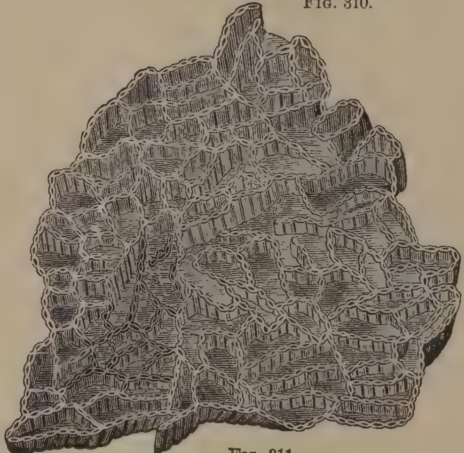

Fig. 311.

Figs. 309–311.—Favositid and Halysitid Corals: 309. Columnaria alveolata: *a*, vertical; *b*, cross-section (after Hall). 310. Syringopora verticillata. 311. Halysites catenulata (after Hall).

Some of the more characteristic species of these families are given above (Figs. 306–311).

There are many other forms than those mentioned above, but their affinities are little understood, and many are not true corals, but Polyzoa and sponges. Nearly all the corals of Silurian, in fact, of Palæozoic times, fall under two orders—*Rugosa* and *Tabulata.* The Cyathophylloids are Rugosa, the other families mentioned are Tabulata. These, though coralloid in form, are probably (like the still-living millipores) *Hydrozoa* (Hydro-corals). The Rugosa are characteristic of the Palæozoic; the Tabulata are also nearly extinct: they have only one family living, viz., the millipores. The Rugosa differ from modern star-corals in having their radiating septa in multiples of four, while modern star-corals have theirs in multiples of five or six. Hence star-corals have been divided into two types—a Palæozoic and a Neozoic—the one four-parted (quadripartita), the other six-parted (sexpartita). Halysitids are characteristic of *Silurian;* Favositids, of *Silurian* and *Devonian;* and Cyathophylloids, of the *Palæozoic.*

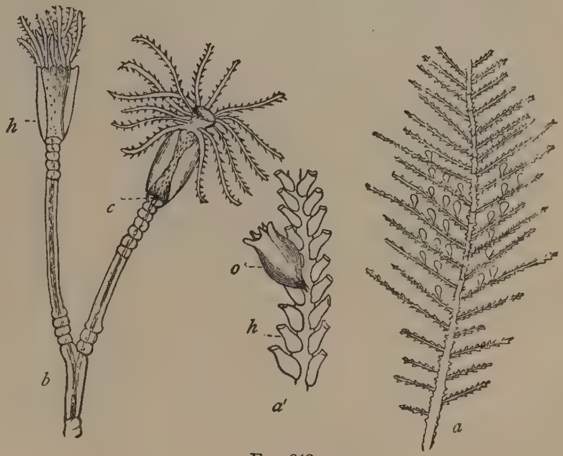

Fig. 312.

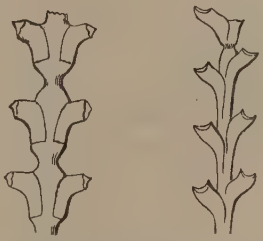

Fig. 313.

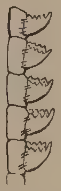

Fig. 314.

Figs. 312-314.—Living Hydrozoa: 312. *a*, Sertularia pinnata; *a′*, same, enlarged *b*, Campanularia. 313. *a* and *b*, Different Forms of Sertularia. 314. Plumularia.

Hydrozoa.—The *perfect* forms of this class, viz., Medusæ, or jellyfishes, are so soft and perishable that they could hardly be expected to be preserved as fossils. Nevertheless some supposed impressions of them have recently been found by Nathorst, even in the lowest Cambrian (Olenellus zone).* But the *larval* form of most, if not all, Medusæ is a compound polypoid animal, forming a minutely-branching, horny, or coralline axis. These minutely-branching axes are strung on one or both sides with cells, in which are inclosed little polypoid animals. They grow in still, quiet waters, and are often mistaken by the unscientific for sea-weed. These, by their composition, are well adapted for preservation, and it is this larval form, therefore, only that we might expect to find. Figs. 312–314 are examples of living forms.

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* Walcott, Tenth Annual Report, U. S. Geol. Surv., p. 587.

Now, in very fine shales of Silurian and Cambrian age are found abundantly beautiful impressions of an organism which is most probably a compound Hydrozoan allied to Sertularia of the present day. They are called *graptolites*. Sometimes the cells are arranged on one side of the axis, sometimes on both sides, sometimes the axis is divided. Whatever be their affinities, they are of great importance, inasmuch as they are *entirely characteristic of this age*, and *those with cells on both sides, of the Lower Silurian and Cambrian*. The twin graptolites (Fig. 317) are also wholly charac-

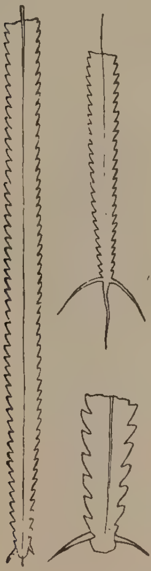


Fig. 315.

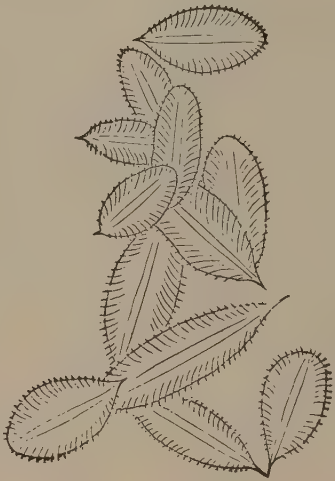


Fig. 316.

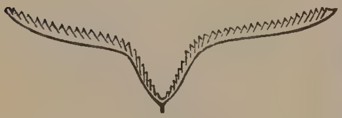


Fig. 317.

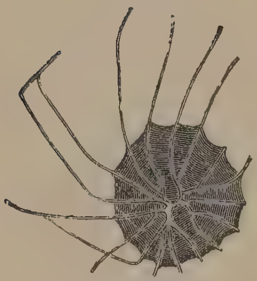


Fig. 318.

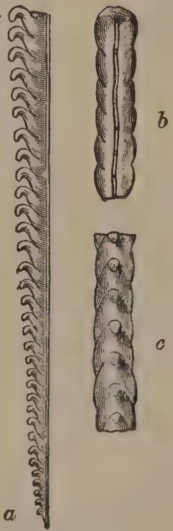


Fig. 319.

Figs. 315–319.—Graptolites: 315. Diplograptus pristis (after Nicholson). 316. Phyllograptus typus (after Hall). 317. Didymograptus V fractus (after Hall). 318. Graptolithus Logani (after Hall). 319. Monograptus priodon: *a*, side view; *b*, back view; *c*, front view, showing opening (after Nicholson).

teristic of Lower Silurian. In Figs. 315 to 321 we give some examples of these characteristic Silurian forms.

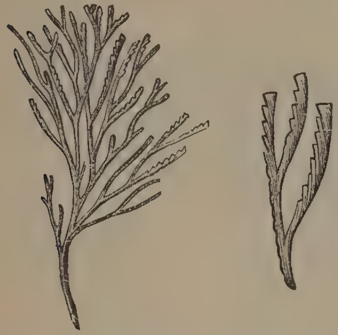


FIG. 320.

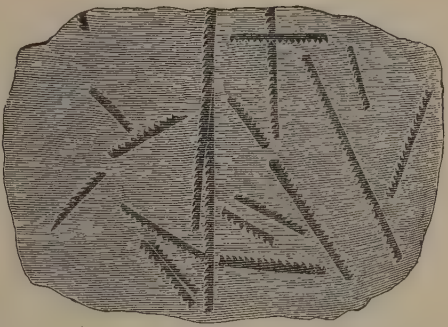


FIG. 321.

FIGS. 320, 321.—GRAPTOLITES: 320. Dendrograptus Hallianus (after Hall). 321. Graptolites Clintonensis (after Hall).

Polyzoa.—There are many kinds of compound coralline animals, probably allied to the Bryozoa (sea-mats) (Fig. 322) of our present seas, found in the Silurian. The doubtful affinities of these Palæozoic forms, and the difficulty of separating them sharply from certain forms of true corals on the one hand, and from certain forms of graptolites on the other, seem to require their notice in this connection, although their affinities are probably molluscoid. Two of the Silurian forms are represented in Figs. 323 and 324.

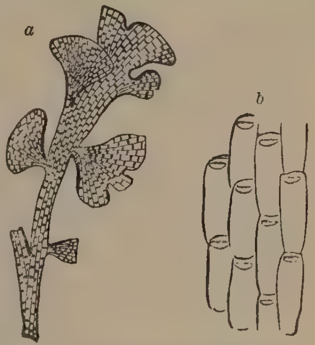


FIG. 322.—Living Polyzoa: Flustra truncata: *a*, natural size; *b*, enlarged to show the cells.

Echinoderms.—During Silurian times the class of Echinoderms was represented principally by *Crinoids*. A Crinoid is a stemmed Echinoderm, usually with branching arms. The animal consists of a long *jointed* stalk, rooted to the sea-bottom, and bearing atop a rounded or pear-shaped body, covered with calcareous plates (calyx), from the margin of which spring the arms, which may be long and profusely branched, or short and simple, or absent altogether. In the middle of the calyx, between the bases of the arms, is placed the mouth. Their general structure and appearance will be better understood by examination of the following figures (325–327) of living Crinoids.

At present, leaving out the Holothurians, or sea-cucumbers, which, having no shell, are little apt to be preserved as fossils, the class of Echinoderms may be conveniently divided into three orders, viz.: the *Echinoids*, or sea-urchins; the *Asteroids*, or star-fishes; and the *Cri-*

noids. The members of the first and second orders are free moving, while those of the third are stemmed. Of these orders the Crinoids are the lowest, as proved not only by their simpler organization, but also by the fact that a living Crinoid, the Comatula or Antedon (Fig. 327), is attached when young, but free when mature.

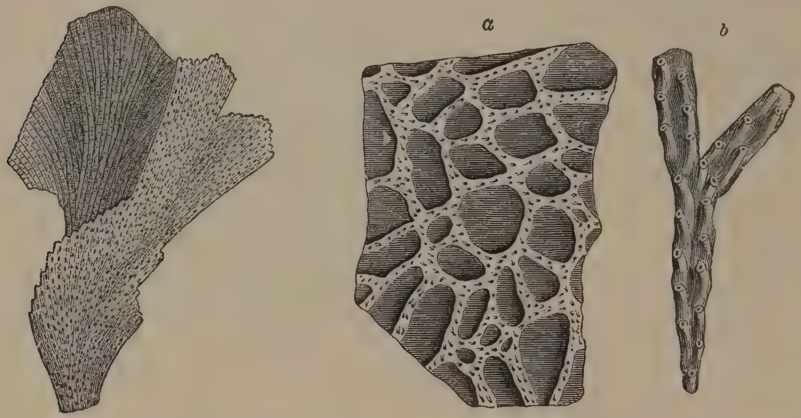


Fig. 323. Fig. 324.

Figs. 323 and 324.—Silurian Polyzoa: 323. Fenestella elegans (after Hall). 324. Alecto auloporoides (after Hall).

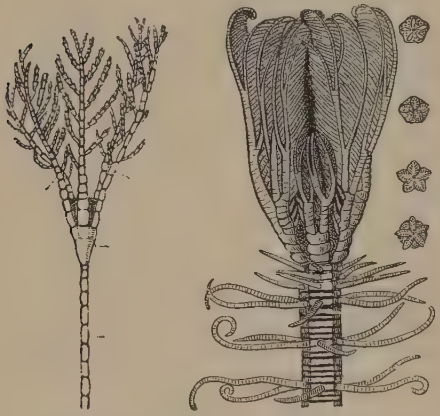


Fig. 325. Fig. 326.

Figs. 325 and 326.—Living Crinoids: 325. Rhizocrinus Lofotensis (after Thompson). 326. Pentacrinus Caput-Medusæ.

Now, during this age the stemmed Echinoderms are very abundant, while the free are very rare: at the present time, on the contrary, the reverse is the case. Thus, in the course of time, the former decreased until they are now almost extinct, while the latter increased until they are now very abundant. If we take the abundance of Echinoderms during geological times as constant, and represent the course of time by the absciss *A B* (Fig. 328), and the abundance by distance from *A B* to *C D*, then the parallelogram would represent this fact. If, now, we draw the diagonal, *C B*, then the shaded triangle would represent the stemmed, and the unshaded the free, and the diagonal the line of decrease of the one and increase of the other; and the whole figure the general relations of the two sub-classes throughout time. In the Palæozoic the stemmed predominate; in the Mesozoic the two are equally represented; in modern times the free predominate.

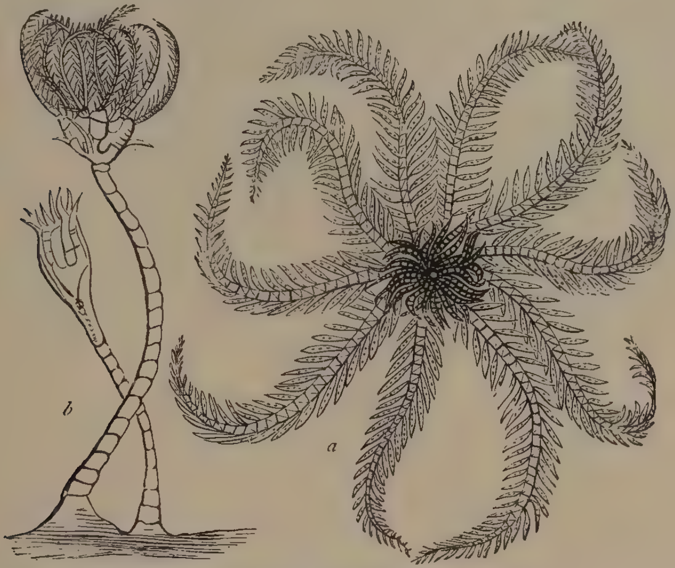


FIG. 327.—A Living Free Crinoid—Comatula (Antedon) rosacea, the Feather-Star: *a*, free adult; *b*, fixed young (after Forbes).

Stemmed Echinoderms, or Crinoids, may be divided into three families, viz.: 1. *Crinids;* 2. *Cystids;* 3. *Blastoids.* *Crinids* are the typical Crinoids, with branching arms (brachiate), already illustrated from living examples (Figs. 325–327). *Cystids* (Figs. 329–332) are of a *bladder*-like form (hence the name), and are either without arms, or else have *few*, *short*, *simple* arms springing from near the center of the upper part of the body, the mouth being probably on one side (abrachiate). The radiated structure in these is imperfect. *Blastoids* (Gr. *βλάστος, a bud*) had a bud-shaped body, with five petalloid spaces

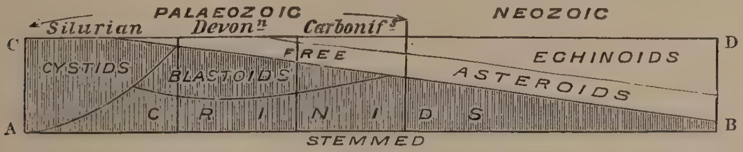


FIG. 328.—Diagram showing the Distribution in Time of the Class of Echinoderms.

(ambulacra) radiating from the top and reaching half-way down the body (see Figs. 530 and 531, page 407). If Crinids are comparable to inverted Star-fishes with many arms and set upon a stalk, the Cystids and

Blastoids may be compared to Sea-urchins similarly set. All these families are found in the Cambrian and Silurian. The Cystids pass away nearly entirely with the Silurian, and may be regarded therefore as characteristic of this age. The Blastoids pass away before the end of the Carboniferous age, and are therefore characteristic of the Palæozoic era, but especially of the Devonian and Carboniferous ages. The distribution of the three orders in time is shown in diagram (Fig. 328). The Crinids continue, though in diminished numbers, to the present day; but of course in very different families. Figures of Blastoids are given under the Carboniferous, where they were far more abundant.

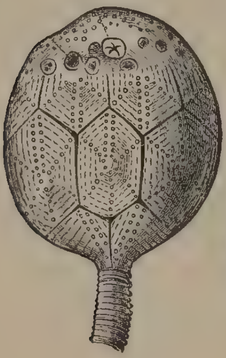
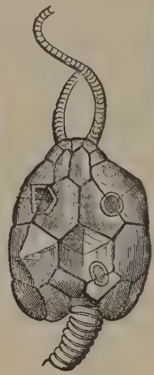


Fig. 329.



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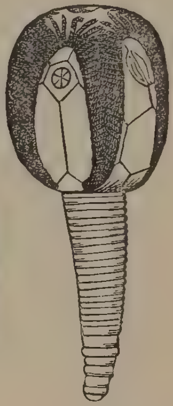


Fig. 331.

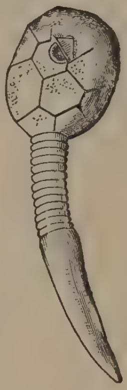


Fig. 332.

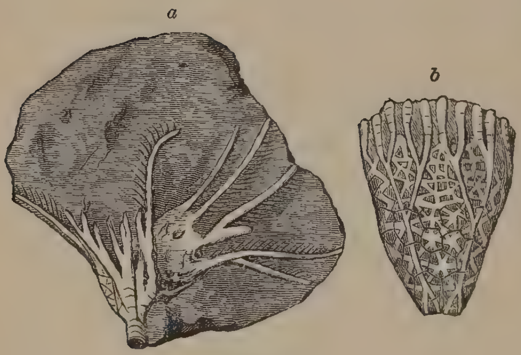


Fig. 333.

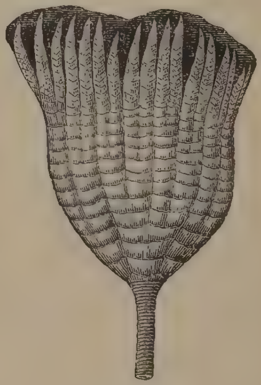


Fig. 334.

Figs. 329–334.—Silurian Crinoids: 329. Caryocrinus ornatus. 330. Pleurocystitis squamosus. 331. Pseudocrinus—a cystid restored (after Lütken). 332. Lepadocrinus Gebhardii. 333. Glyptocrinus decadactylus (after Hall): *a*, specimen with arms; *b*, larger specimens without the arms. 334. Ichthyocrinus sublævis (after Hall).

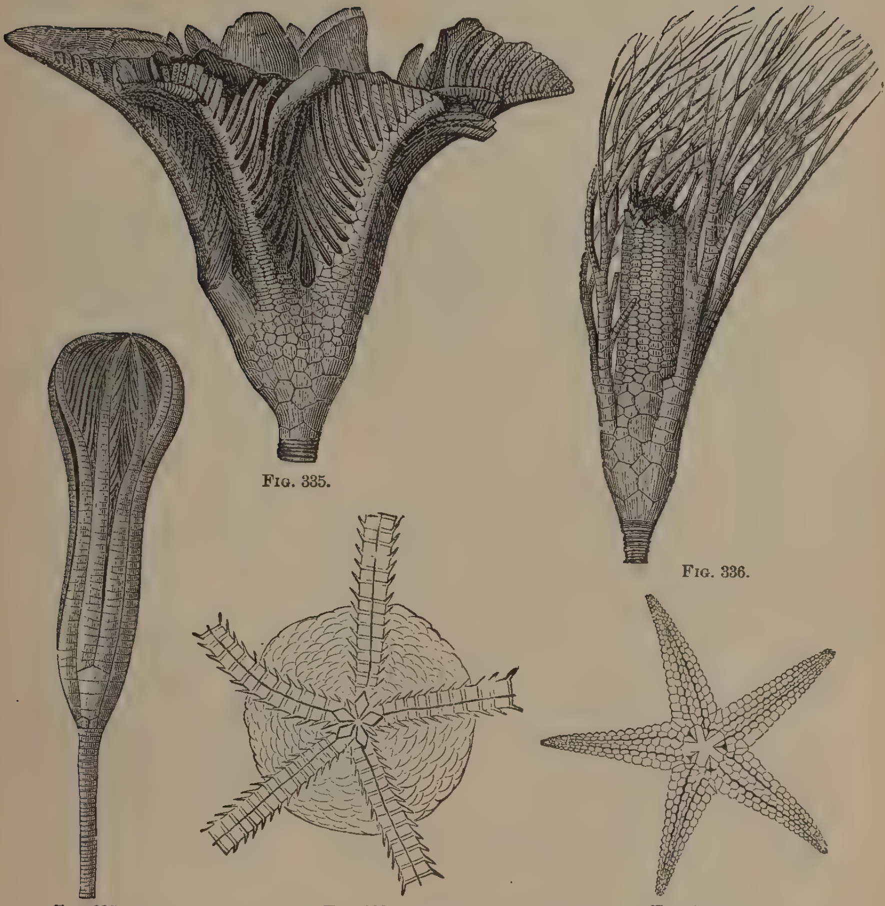


FIG. 335. FIG. 336. FIG. 337. FIG. 338. FIG. 339.

FIGS. 335–339.—SILURIAN CRINOIDS AND ASTEROIDS: 335. Mariacrinus nobilissimus (after Hall). 336. Homocrinus scoparius (after Hall). 337. Heterocrinus simplex (after Meek). 338. Protaster Sedgwickii. 339. Palæaster Shæfferi (after Hall).

Mollusks—*Brachiopods.*—Bivalves may be divided into two great sub-classes, viz., *Lamellibranchs* (leaf-gills) and *Brachiopods* (arm-feet). The valves of Lamellibranchs are *right and left;* those of Brachiopods are *upper and lower*, or dorsal and ventral. Brachiopods are much less highly organized than the other sub-class, and differ so essentially in their organization that some of the best naturalists remove them not only from the class of Acephals, but from the *department* of Mollusca, and ally them rather with the *Worms*. Their general resemblance in external form to bivalves makes it more convenient to treat them under that head, until the question of their affinity is more definitely settled. Brachiopods are abundant in the Cambrian

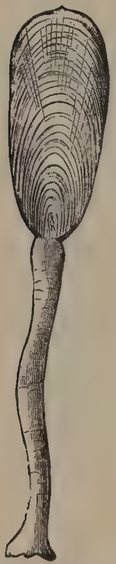


Fig. 340. — Lingula anatina, showing the muscular peduncle by which the shell is attached.

and still more so in the Silurian. About 2,000 species are known from the Silurian alone (Miss Crane).

General Description of a Brachiopod.—A Brachiopod shell consists of two valves, a dorsal and a ventral. The ventral is the larger, and usually projects beyond the dorsal, at the hinge, as a prominent beak. This projecting portion is often perforated to give passage to a muscular peduncle, by which the shell is attached in the living animal. The following figures (Figs. 340–348) of Brachiopods, living and extinct, will make these points clear.

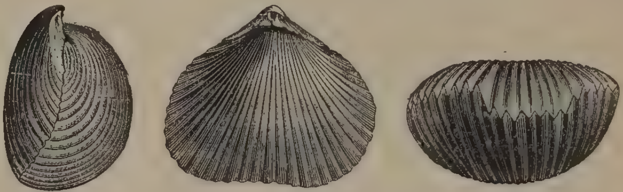


Fig. 341.—Rhynchonella sulcata: side view, dorsal view, and end view, showing suture.

The viscera of a Brachiopod fill but a small space in the shell, this cavity being occupied

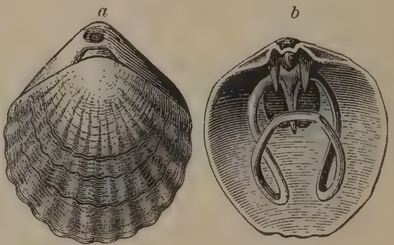


Fig. 343.

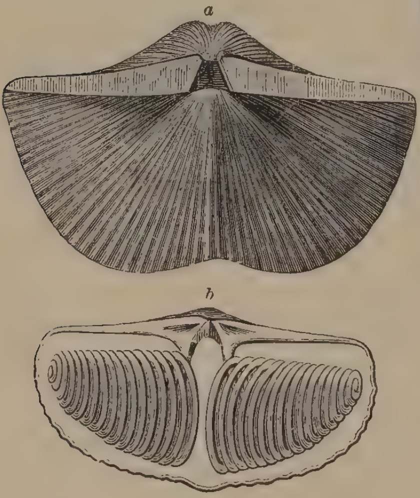


Fig. 342.

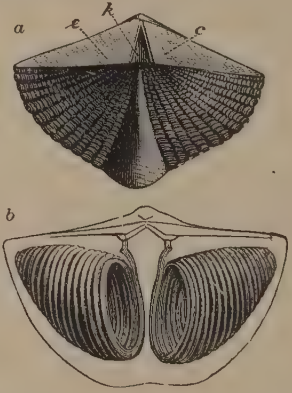


Fig. 344.

Figs. 342–344.—Showing the Structure of Brachiopods: 342. Spirifer striatus (Carboniferous): *a*, dorsal surface; *b*, interior, showing the bony spirals. 343. Magellania flavescens (living species): *a*, exterior surface; *b*, showing bony structure for attachment of spiral arms. 343. Spirifer hysterica (Carboniferous): *a*, exterior; *b*, showing bony spires.

principally by two long spiral arms (hence the name), which probably subserve the functions of respiration and alimentation. These arms are attached to a curious bony apparatus, sometimes in loops (Fig. 343) and sometimes itself spiral in form (342 and 344). Figs. 342–344 show the internal structure described above.

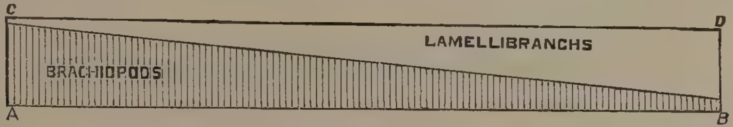


Fig. 345.—Diagram showing the General Relation in Time of Brachiopods to Lamellibranchs.

In the present seas the Lamellibranchs are extremely abundant while the Brachiopods are nearly extinct, being represented by comparatively few species. In Silurian times, on the contrary, the very reverse is the case, bivalve shells being represented mostly by Brachiopods. Taking the number of bivalve species throughout geological times as constant, then the general relation of these two sub-classes to each in time may be roughly represented by the diagram, Fig. 345, in which the lower triangle represents Brachiopods, the upper Lamellibranchs, and the common diagonal the line of decrease of one and increase of the other.

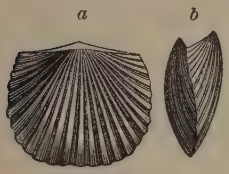


Fig. 346.

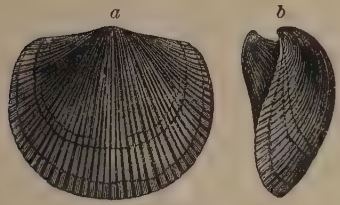


Fig. 347.

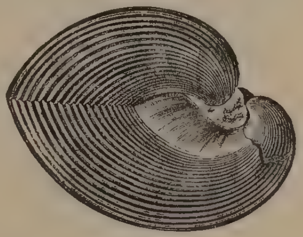


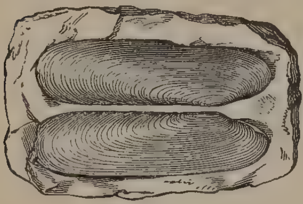
Fig. 348.

Figs. 346–348.—Silurian Brachiopods: 346. Orthis Davidsonii. 347. Orthis porcata. 348. Pentamerus Knightii.

The abundance of individuals and the number of species of this order in Silurian times are almost incredible. The accompanying figures represent some of the common and characteristic forms.

It is very difficult to give any general distinctive mark of *Silurian* Brachiopods, although, of course, the species and even the genera are peculiar, and may be recognized by the palæontologist. It may be said, however, that the *straight-hinged* or *square-shouldered* Brachiopods, including the Spirifer family, the Strophomena or Leptena family, and the Productus family, are characteristic of the Palæozoic, though not of the Silurian.

Lamellibranchs.—We have said that Lamellibranchs are also found in the Silurian and even the Cambrian, but not so abundantly as the Brachiopods. Lamellibranchs are divided into Siphonates and Asiphonates, i. e., those with and those without breathing-siphons behind. The Siphonates are the higher. At present the Siphonates are the more abundant—in Palæozoic times the Asiphonates. The accompanying figures (349–353) are examples of Silurian Lamellibranchs.



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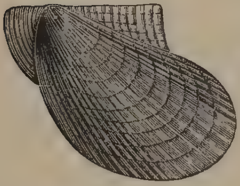
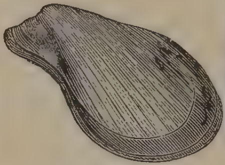


Fig. 350.



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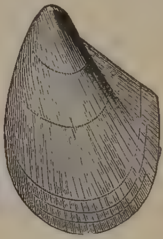

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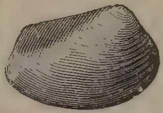


Fig. 353.

Figs. 349-353.—Silurian Lamellibranchs: 349. Orthonota parallela. 350. Cardiola interrupta (after Hall). 351. Avicula Trentonensis (after Hall). 352. Ambonychia bellistriata (after Hall). 353. Tellenomya curta (after Hall).

Gasteropods—*Univalves.—Land* and *fresh-water* Gasteropods have not been found in the Silurian. If we divide marine Gasteropods or univalves into those having beaked shells and those having smooth-mouthed or beakless shells, the former being carnivorous and the latter herbivorous, then only the smooth-mouthed or beakless shells have been found in the Silurian. The beak-shelled are usually regarded as the more highly organized class. The affinities of Conularia (Fig. 360) are little understood. They are usually placed among Pteropods.

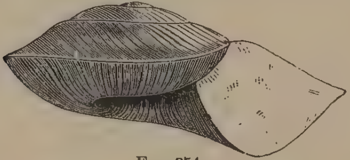
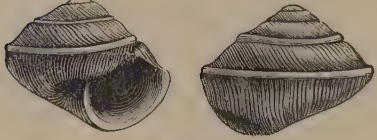


Fig. 354.



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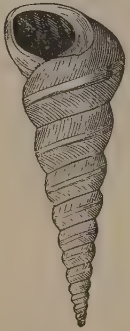


Fig. 356.

Figs. 354–356.—Silurian Gasteropods: 354. Pleurotomaria dryope. 355. Pleurotomaria agave. 356. Murchisonia gracilis.

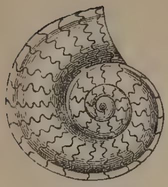


Fig. 357.

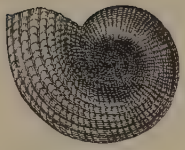
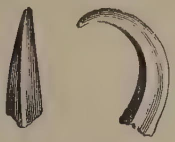


Fig. 358.



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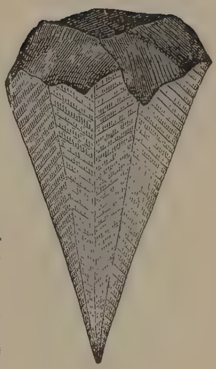

Fig. 360.

Figs 357–360.—Silurian Gasteropods and Pteropods: 357. Cyrtolites compressus (after Hall). 358. Cyrtolites Trentonensis (after Hall). 359. Cyrtolites Dyeri (after Meek). 360. Conularia Trentonensis (after Hall), a Pteropod.

Cephalopods—*Chambered Cells.*—These are by far the most highly organized of Mollusks, and the most powerful among Invertebrates. They are represented in the present seas by the Nautilus, the Squids, and the Cuttle-fishes. If we divide all known Cephalopods, living and fossil, into *Dibranchs* (two-gilled) and *Tetrabranchs* (four-gilled), the former being *naked* and the latter *shelled*, then, at the present time, the Dibranchs, or naked, vastly predominate, there being only a single genus of shelled or Tetrabranchs known, viz., the Nautilus, and of this genus only three or four species. In the Silurian age, and for many ages afterward, *only the shelled* existed. The naked or Dibranchs are decidedly the higher in organization.

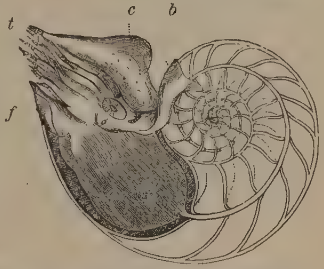

Fig. 361.—Pearly Nautilus (Nautilus pompilius): *a*, mantle; *b*, its dorsal fold; *c*, hood; *o*, eye; *t*, tentacles; *f*, funnel.

Again, if we divide chambered shells into those having *simple* septa and *central* or subcentral tube or siphuncle (Nautiloid), and those having septa plaited at their junction with the shell (plaited suture) and *ventral** tube (ammonoid), then in this age the former only were represented.

Again, if we divide the Nautiloids into *straight*-shelled and *coiled*-shelled, then the straight chambered shells greatly predominated. Straight chambered shells are called Orthoceratites (ὀρθός, *straight ;* κέρας, horn). The Orthoceratites, therefore, are a very striking feature of the Silurian age. They may be defined as straight chambered shells, with simple sutures and a central or subcentral siphon-tube (siphuncle). The siphuncle of the family was large in proportion to the shell, and had often a beaded structure (Fig. 362, *a*, *b*, *c*, *d*). The genera are founded largely on the form of this part.

They existed in great numbers, and attained very great size. Specimens have been found fifteen feet long, and eight to ten inches in diameter. They were, without doubt, the most powerful animals of that time, the tyrants and scavengers of these early seas. We give in Fig. 363, a restoration of the creature. They are entirely characteristic of the Palæozoic; commencing in the Primordial, extending through into the Carboniferous, and passing out there. They attained their maximum of development in size and number in the Silurian.

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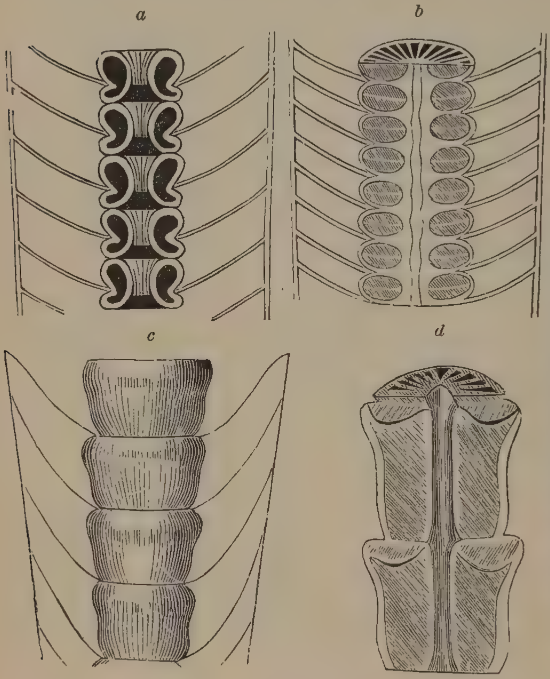
* The outside of the whorl is usually called dorsal, but it is now known to be *ventral.*



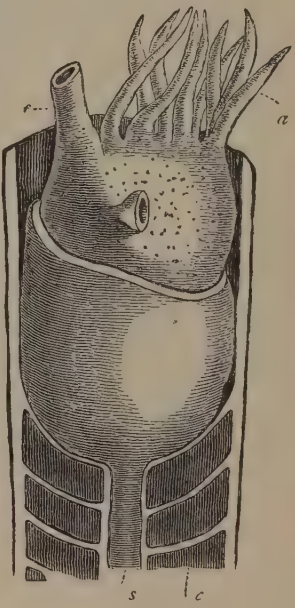


Fig. 362. Fig. 363.

Fig. 362.—Showing Structure of Orthoceratite: *a*, Ormoceras; *b*, Actinoceras; *c*, Huronia; *d*, Section of Siphuncle of Huronia.

Fig. 363.—Restoration of Orthoceras, the shell being supposed to be divided vertically, and only its upper part being shown: *a*, arms; *f*, muscular tube ("funnel") by which water is expelled from the mantle-chamber; *c*, air-chambers; *s*, siphuncle (after Nicholson).

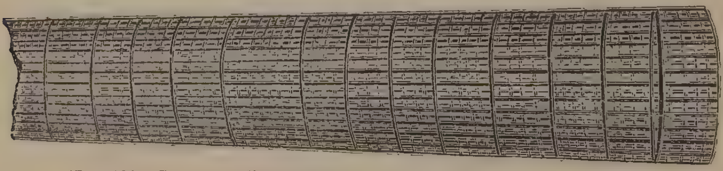


Fig. 364.—Silurian Cephalopod: Orthoceras medullare (after Meek).

Although straight chambered shells (Orthoceratites) are most abundant and characteristic, and also the earliest, coiled shells of the same tribe (Nautiloids) are also found, and some of them of considerable size, but not until the upper Silurian. Some of these are close-coiled shells, true Nautilus family; others open-coiled, and more nearly allied

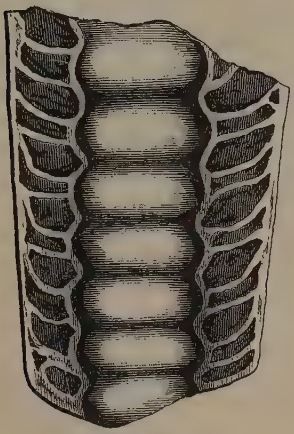


FIG. 365.

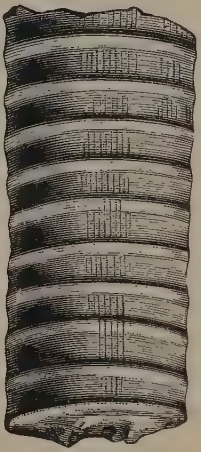


FIG. 366.

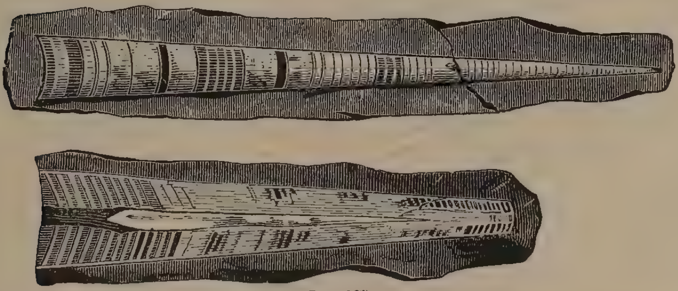


FIG. 367.

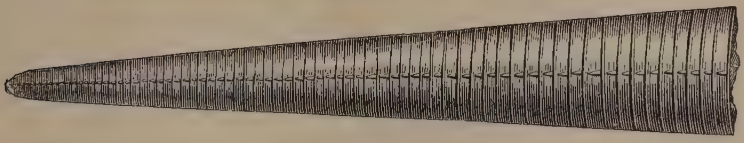


FIG. 368.

FIGS 365–368.—SILURIAN CEPHALOPODS: 365. Ormoceras tenuifilum, showing chambers and siphuncle (after Hall). 366. Orthoceras vertebrale (after Hall). 367. Orthoceras multicameratum (after Hall). 368. Orthoceras Duseri (after Hall).

to the straight. The gradual change from the straight through the open-coiled to the close-coiled may be traced. It is a most significant fact that the Nautilus in its embryonic development passes through all these stages—i. e., it is first straight, then bent, then open-coiled, and finally close-coiled (Hyatt). Barrande gives 1,622 species of Cephalopods in the Silurian.

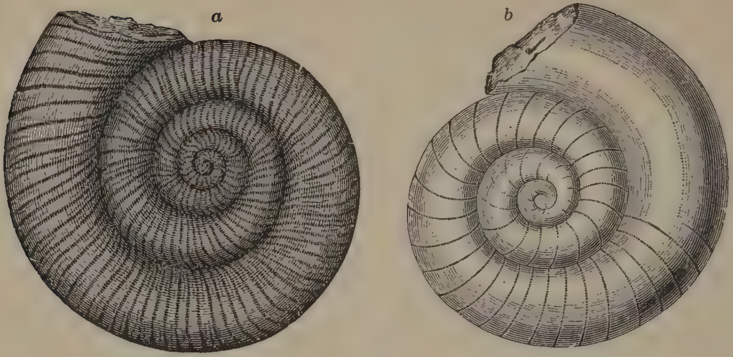
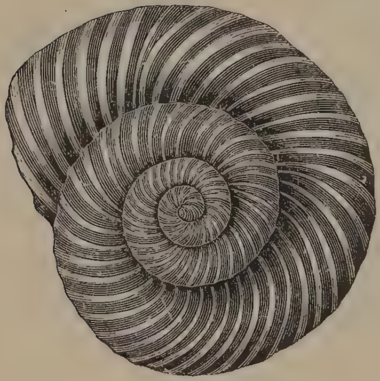


FIG. 369.



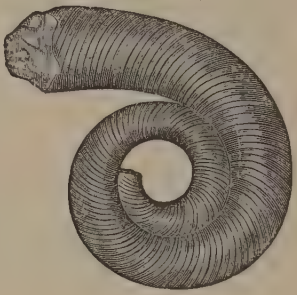


FIG. 371.

FIG. 370.

FIGS. 369–371.—SILURIAN CEPHALOPODS: 368. Trocholites Ammonius (after Hall): *a*, exterior; *b*, cast, showing septa. 369. Lituites Graftonensis (Meek and Worthen). 370. Lituites cornu-arietis.

Worms.—These are fleshy animals without skeletons, and are therefore not preserved. They are known only by their *tracks*, their *borings*, their tubes, and, more rarely, their teeth. Nevertheless, some 185 species, according to Barrande, have been described from the Silurian of different countries. Fig. 372 represents worm-tubes, Fig. 372 worm-tracks, and Fig. 374 worm-teeth from the Silurian.

Crustacea—*Trilobites.*—The principal representatives of the Arthropods in Cambrian and Silurian times were *Crustaceans*, but mostly of a very characteristic order of that class, now long extinct, viz., *Trilobites.*

General Description.—The carapace or shell of these curious creatures was convex and usually smooth above, and flat or concave below, and divided transversely, like most crustacea, into a number of movable joints. Several of the front joints are *always* consolidated to form a head-shield or *Buckler*, and *sometimes* a number of the posterior joints are similarly consolidated to form a tail-shield or Pygidium. The whole shell or carapace is divided longitudinally, more or less distinctly, into three lobes (hence the name)—a middle, a right, and a left. Some characteristic forms of silurian trilobites are shown in Figs. 376–

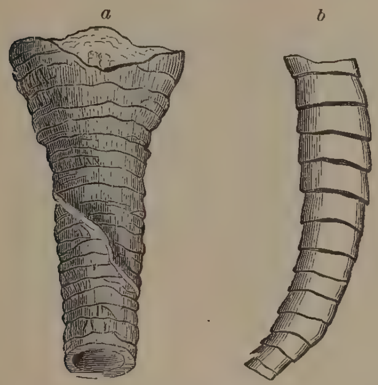


Fig. 372.

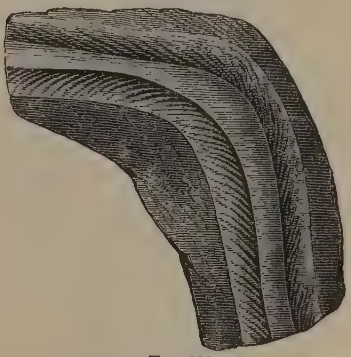


Fig. 373.

Figs. 372, 373.—Silurian Annelids: 372. Cornulites serpentarius (Worm-Tube). 373. Trail of an Annelid (after Hall).

381. The viscera were contained in the middle lobe, the two side lobes being extensions of the shell, as seen in the section, Fig. 384, *A* and *B*. Well-organized compound eyes are distinctly seen in well-preserved specimens on the lateral lobes of the head-shields (cheeks) (Fig. 375). The under side of the animal has never been distinctly seen. It

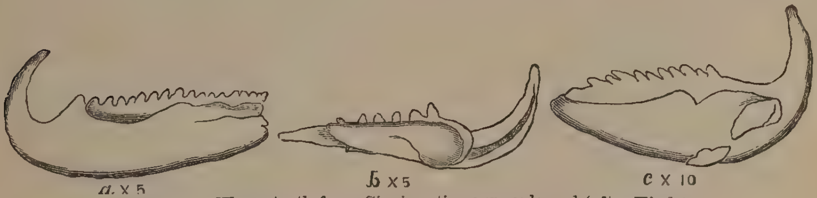


Fig. 374.—Worm-teeth from Cincinnati group, enlarged (after Hinde).

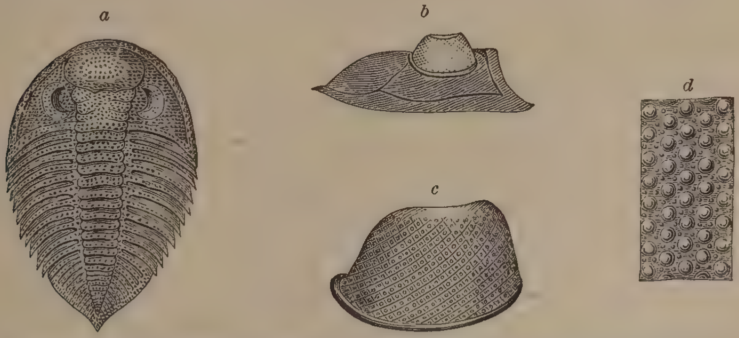


Fig. 375.—Structure of the Eye of Trilobites: *a*, Dalmania pleuropteryx; *b*, eye slightly magnified; *c*, eye more highly magnified; *d*, small portion still more highly magnified (after Hall).

was formerly supposed, however, that like many lower crustaceans of the present day (Phyllopods) their limbs were mostly or wholly

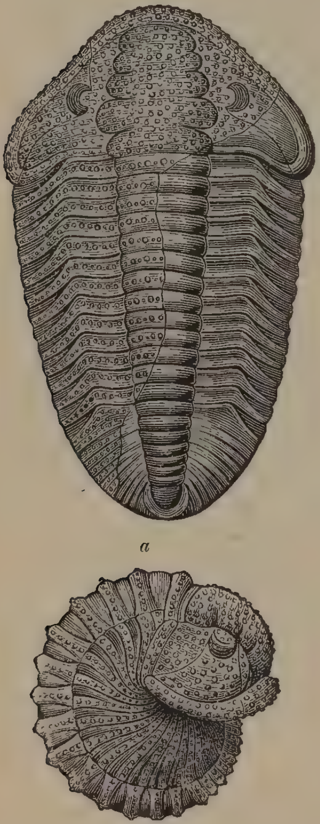


Fig. 376.

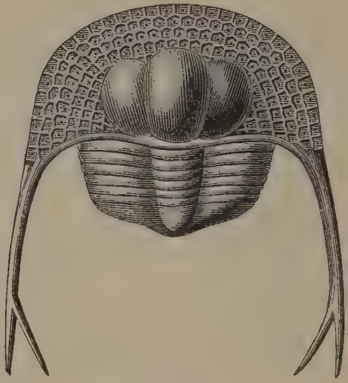


Fig. 377.

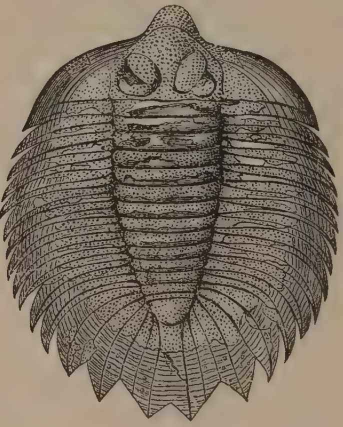


Fig. 378.

Figs. 376–378.—Silurian Trilobites: 376. Calymene Blumenbachii; *a*, Same in folded condition. 377. Trinucleus Pongerardi. 378. Lichas Boltoni (after Hall).

leaf-like swimmers. In 1876 Walcott proved the existence of articulated legs. In 1893 beautifully preserved specimens of Triarthrus were found in the Utica slate, near Rome, N. Y., and described by Matthew, in which not only legs were more perfectly displayed, but what was not before suspected, a pair of slender many-jointed *antennæ.* Each locomotive appendage was double, one branch for crawling and one for swimming and probably breathing. The antennæ were attached on the under surface of the head. These facts are shown in the restorations, Fig. 382, *A* and *B*, in which *A* shows the dorsal and *B* the ventral aspect of the animal. Fig. 383, *a* and *b*, show the limbs enlarged, and Fig. 384, *A* and *B*, are diagrammatic sections—*A* through the thorax, *B* through

Pygidium, showing the structure and position of the limbs. We are indebted to Prof. Beecher for the splendid restorations of Triarthrus, shown in Fig. 382.

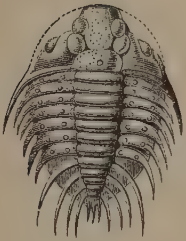


Fig. 379.

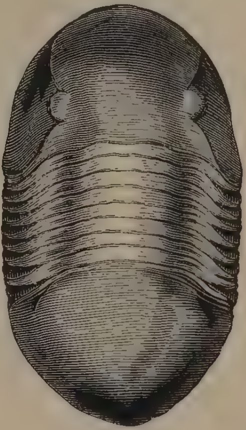


Fig. 380.

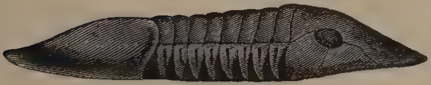


Fig. 380 *a*.

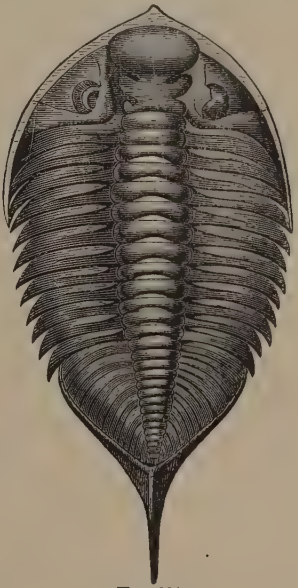


Fig. 381.

Figs. 379–381.—Silurian Trilobites: 379. Acidaspis crosotus (after Meek). 380. Isotelus gigas, reduced (after Hall). 380 *a*. Same, side-view. 381. Dalmanites limulurus.

It is easy to see why the under side is never exposed; for the mud, in which they were entombed, would become entangled among these leaf-like swimmers and numerous slender legs, and in breaking the rock this would determine the line of fracture over the smooth back, and leave the creature firmly attached by its ventral surface to the lower piece. Not uncommonly Trilobites are found folded up on their ventral surface, so as to bring head and tail together and form a kind of ball. In such cases the Trilobite may be got out of the rocky matrix complete; but none the less are the feet completely hidden (Fig. 376, *a*).

The great number of genera into which this large order is divided is founded principally on the form and sculpturing of the Buckler, the size and form of the Pygidium, the number of the movable segments, etc. The figures will give an idea of some of these forms.

It is very interesting to observe that a complex mechanism, the compound eye like that of crustaceans and insects of the present day, was already developed even in the early Primordial times.

Trilobites commenced, as already stated, in the earliest Primordial, continued through the whole Palæozoic, and then became extinct forever. They are therefore entirely characteristic of the Palæozoic. They reached their maximum of development, in size, number, and variety, in the Silurian. Barrande gives the number of species described in the Silurian alone as 1,579. They reached in some cases a size equal to any crustaceans now living. The *Asaphus* (*Isotelus*) *gigas*, from the Lower Silurian (Fig. 380), was sometimes twenty inches in length and thirteen wide. Parodoxides (Figs. 292 and 293, p. 313), of the earliest Primordial, attained a length of twenty-two inches. On account of their great abundance and fine preservation, their embryonic development has been carefully studied by Barrande, who has described and figured twenty steps in the development of some species (Fig. 385). According to Agassiz, we know nearly as much of the development of Trilobites as of any living crustacean.

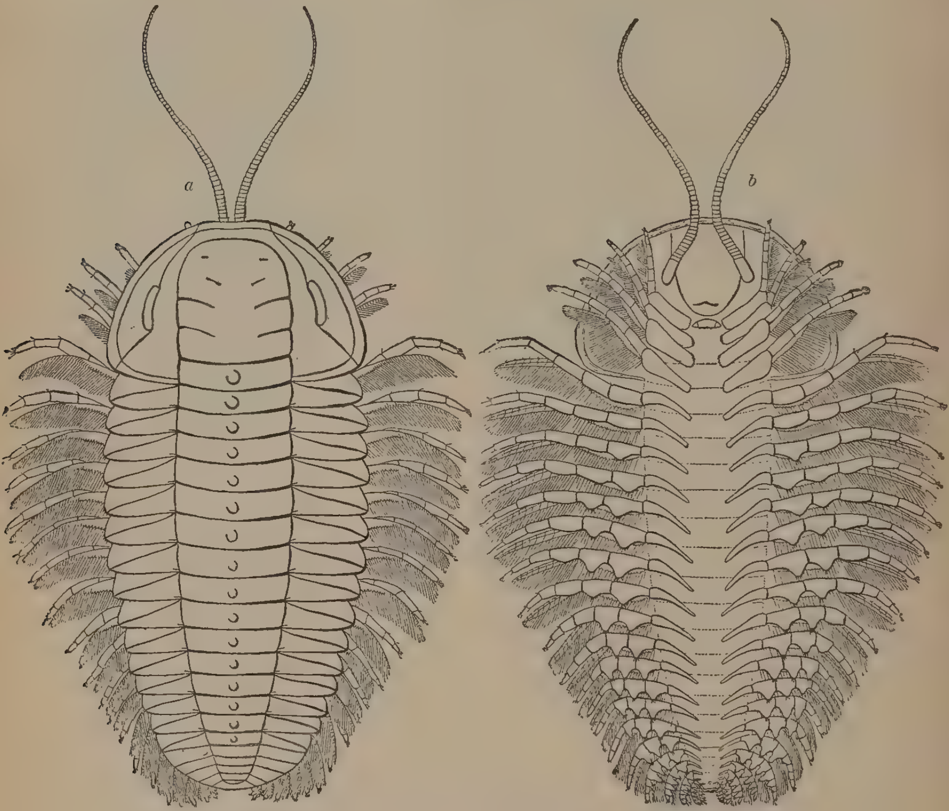


FIG. 382.—Triarthrus Becki, restored by Beecher, showing limbs and antenæ; *a*, Dorsal; *b*, ventral surface.

Affinities of Trilobites.—The affinities of this very distinct order are imperfectly understood. Crustaceans are divided into two sub-classes, a higher, *Malacostraca* (mollusk-shelled or calcareous-shelled), and a lower, *Entomostraca* (insect-shelled). Now, Trilobites, though belonging to the lower division, or Entomostraca, occupy a position near the confines of the two divisions. More definitely, they probably stand between the *Isopods* (tetradecapod Malacostracans), on the one hand, and the *Phyllopods* and *Limuloids* (Entomostracans), on the other. In general appearance they certainly approach Limuloids (horseshoe-crabs or king-crabs), and these seem to have replaced them in the process of evolution. They are by no means very low in the scale of crustaceans; their position being near the middle. The larvæ of crustaceans, especially of Limuloids, greatly resemble some forms of Trilobites, and especially the larvæ of Trilobites.

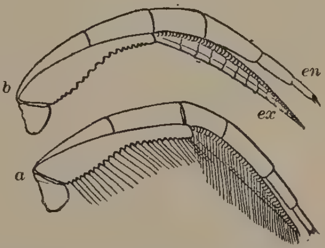


FIG. 383.—Limbs of Triarthrus Becki enlarged. In *b* the setæ are removed to show structure; *ex*, exopodite; *en*, endopodite (after Beecher).

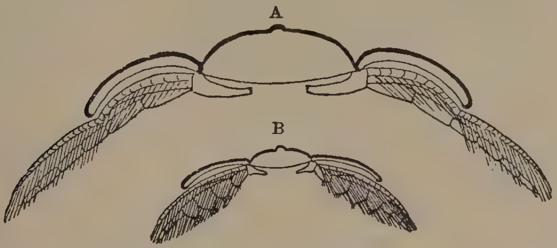


FIG. 384.—Transverse section of Triarthrus: A, through thorax; B, through pygidium; showing structure and position of the limbs (after Beecher).

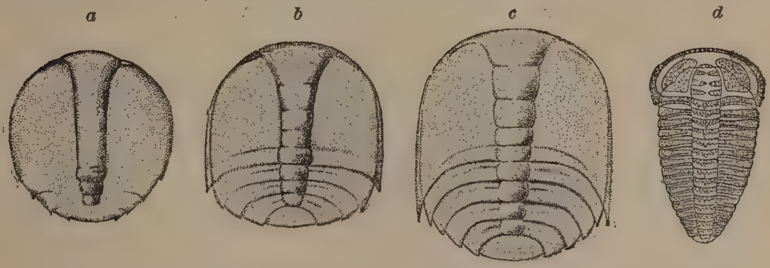


FIG. 385.—Sao hirsuta: *a*, *b*, *c*, larval stages, + 30; *d*, adult, + ½ (after Barrande).

From early generalized forms somewhat like the larvæ represented by Fig. 385 there have been probably differentiated, in one direction the more perfect Trilobites, and in the other the higher forms of crustaceans.

Eurypterids.—In the Upper Silurian was introduced and continued to exist along with Trilobites, during the rest of the Palæozoic, another family of huge Entomostracans probably in advance of Trilobites in organization, viz., *Eurypterids*. The family includes the two genera *Eurypterus* (broad wing) and *Pterygotus* (winged ear). Some of the latter are the largest crustaceans known. The huge Japan crab (*Inachus Koempferi*), with carapace sixteen inches in diameter, and legs four feet long, and the Moluccas king-crab (*Limulus Moluccanus*), three feet long and eighteen inches across the carapace, are the largest crustaceans now living. But the Eurypterids were some of them far greater. The *Pterygotus Anglicus* (Fig. 386) was six feet long and one foot wide, and the *Pterygotus Gigas* seven feet long and proportionately wide. The above figures (386–388) represent some species of these two genera from the American and English rocks.

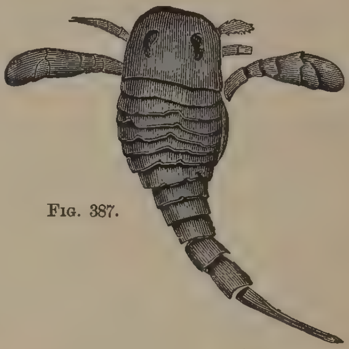


Fig. 387.

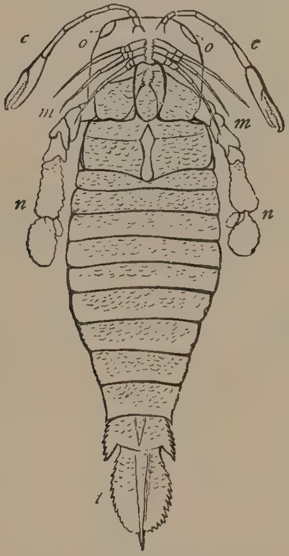


Fig. 386.

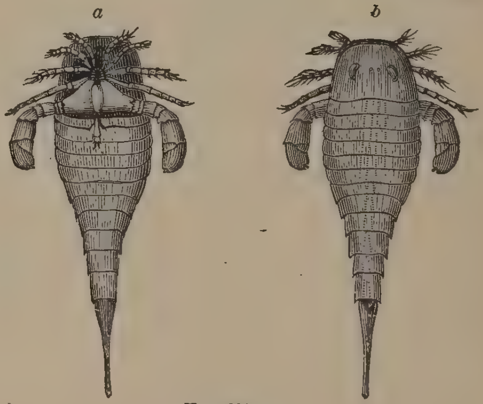


Fig. 388.

Figs. 386–388.—Silurian Eurypterids: 386. Pterygotus Anglicus, viewed from the under side, reduced in size, and restored: *c c*, the feelers (antennæ), terminating in nipping-claws; *o o*, eyes; *m m*, three pairs of jointed limbs, with pointed extremities; *n n*, swimming-paddles, the bases of which are spiny, and act as jaws—Upper Silurian, Lanarkshire (after Henry Woodward). 387. Eurypterus remipes, greatly reduced. 388. Same restored: *a*, dorsal view; *b*, ventral view (after Hall).

Anticipations of the Next Age.—There are some plants and animals still higher than those mentioned above, but they are so rare that it is best to treat them as anticipations of the next age. The most important of these may be briefly noted: 1. A few very small land-plants (Ferns and Club-Mosses) have been found in the upper part of the Lower Silurian of this country and of Europe. 2. A few small air-breathers (insects, Blattidæ and Scorpions) have been found in the Upper Silurian — also of both countries, and recently one (Protocimex) in the upper part of the Lower Silurian. We give a figure of one of these very important discoveries (Fig. 389). That they were really air-breathers is shown by the spiracles or breathing-pores, *a*. 3. A few, small, curiously-formed fishes, of very low organization, somewhat similar to some (Pteraspis) in the Lower Devonian, have recently been found as low as the Clinton group (lower part of the Upper Silurian). We give in Fig. 390 a restoration by Claypole of one of these Upper Silurian fishes.* Such anticipations are in accordance with the law already mentioned (p. 291), that the characteristics of an age often commence in the preceding age.

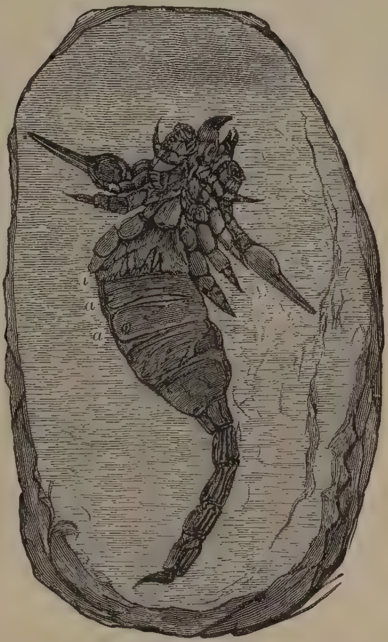


Fig. 389.—Palæopternus—a Fossil Scorpion from Upper Silurian of Scotland (after Peach).

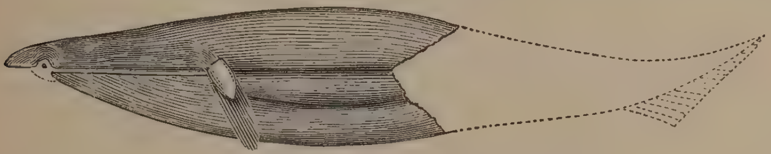


Fig. 390.—Palæaspis Americana, × ⅔ (after Claypole).

It is better, however, to treat of these classes in connection with the age in which they culminate, or at least become a striking feature.

The Silurian was, therefore, essentially an age of Invertebrates. In number, size, and variety, these have scarcely been surpassed in any subsequent period. The most characteristic orders were: Among plants, Fucoids; among animals, Cyathophylloid and Tabulate Corals, Graptolites, Cystidean Crinoids, Square-shouldered Brachiopods, Beakless Gasteropods, Orthoceratites, and Trilobites. Orthoceratites and Trilobites were the highest animals of the age, and the former were the rulers and scavengers of these early seas. We give below a table showing, according to Barrande, the number of Silurian species described up to 1872:

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* Still lower findings are reported, e. g., that of Walcott from rocks of supposed Trenton age (Lower Silurian). But there is some doubt whether the rocks are really Silurian; for the fishes are not even of Lowest Devonian, but of full Devonian type.

Sponges and other Protozoans	153	Brachiopods	1,567
Corals	718	Lamellibranchs	1,086
Echinoderms	588	Heteropods	390
Worms	185	Pteropods	
Trilobites	1,579	Gasteropods	1,306
Other Crustaceans	348	Cephalopods	1,622
Bryozoans	478	Fishes	40

Which, with four of uncertain relations, make 10,074 species. The number has been greatly increased since that time.

Section 2.—Devonian System and Age of Fishes.

The name Devonian was given to these rocks by Murchison and Sedgwick, because in Devonshire the system occurs well developed, and abounds in fossils. In England the system is usually unconformable with the underlying Silurian, and sometimes with the overlying Carboniferous, as in Fig. 391. But in the Eastern United States, as already stated, the Palæozoics are conformable throughout (Fig. 267).

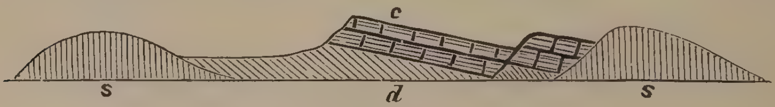


Fig. 391.—*s*, Silurian; *d*, Devonian; *c*, Carboniferous (after Phillips).

Area in United States.—The area over which the Devonian appears as a country rock in the Eastern United States is shown in map, page 302. It borders generally the Silurian on the south and southwest, extending with it far southward in the middle region, viz., in Indiana, Western Ohio, and Kentucky. It borders also the Silurian strip in the Appalachian region. In the Basin Range region, especially about White Pine, Nevada, Devonian is known to exist, but the limits of these areas are too imperfectly known to be described. Recently it has been found also in Siskiyou County, Cal.

Physical Geography.—In the eastern portion of the United States the land of the Devonian age was approximately that of the Silurian age already described, increased by the addition of the Silurian area, which Silurian was of course so much marginal sea-bottom exposed by upheaval during and at the end of Silurian times. There was also a large island in the Devonian seas in the region about Cincinnati, viz., the Silurian area, situated there (see map, p. 302). In the Plateau region there was a large extent of land in later Silurian and Devonian times, as shown by the *absence* of strata of these times in the Grand Cañon section. At the end of Devonian times the Devonian area was added to the existing land, and the continental mass was further increased.

Subdivision into Periods.—In the United States the following four periods are usually recognized:

4. Chemung period.
3. Hamilton period.
2. Corniferous period.
1. Oriskany period.

We shall, however, neglect these subdivisions in our general description of the life of the age.

Life-System of Devonian Age—Plants.

It will be remembered that during the Silurian age, except a few small vascular cryptogams, the only plants found were Fucoids. These continued, though under different species, in Devonian times. But, in addition to these, were now introduced *land-plants* in considerable numbers and variety, and decided complexity of organization. They included all the orders of vascular cryptogams, viz., *Ferns*, *Lycopods*, and *Equisetæ;* and also *Conifers* among gymnospermous Phænogams; and by their great size and numbers probably formed for the first time in the history of the earth a true *forest vegetation.*

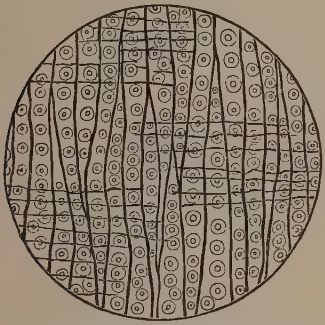


FIG. 392.—Microscopic Section of the Silicified Wood of a Conifer (*Sequoia*), cut in the long direction of the fibers. Post-tertiary? Colorado (after Nicholson).

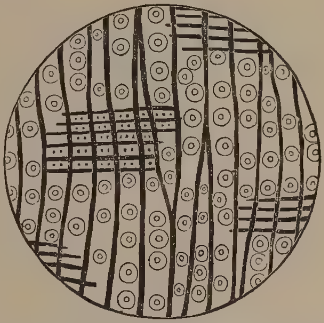


FIG. 393.—Microscopic Section of the Wood of the Common Larch (*Abies larix*), cut in the long direction of the fibers. In both the fresh and the fossil wood (Fig. 389) are seen the disks characteristic of coniferous wood (after Nicholson).

The Ferns were represented by several genera, such as Cyclopteris and Neuropteris: the Lycopods (club-mosses) not only by the Psilophyton, which had been already introduced in the uppermost Silurian, but also now by gigantic *Lepidodendrids* and *Sigillarids*, and the Equisetæ by Calamites and Asterophyllites. The Conifers were represented by the genus *Protaxites*, allied to the *yew* (Taxus). They are known to be conifers by their concentric rings of growth (undoubted traces of which have been found) and gymnospermous tissue, i. e., the elliptic disk-like markings on the walls of the wood-cells on longitudinal section (Figs. 392 and 393), and the entire absence on *cross*-section of the visible pores so characteristic of dicolytedonous Exogens (Fig. 394). Some of these conifers have been found by Dawson eighteen inches in diameter. There have been fifty species of land-plants of these various orders found by Dawson in the Devonian of Nova Scotia alone. In Figs. 395–405 we give the most characteristic Devonian land-plants.

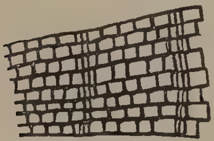


FIG. 394.—Pine-Wood, Cross-Section magnified.

General Remarks on Devonian Land-Plants.—We will not at present discuss the affinities of these plants, and their relations to evolution, because they are similar to those found in the *coal*, where they exist in far greater variety and abundance, and the subject will be discussed under that head. There are, however, some thoughts suggested by the first appearance of highly-organized plants which ought not to be omitted:

1. The ringed structure of Devonian conifers shows that, at that time, there was a growing season and a season of rest, and therefore, probably, a warm and a cold season.

2. What were the precursors of this highly-organized forest vegetation? That there *were* precursors, from which these were derived, there can be no doubt, for we have already found them in the Upper Silurian; but that the *steps of evolution* were just at this point *somewhat rapid*, seems also certain. It is impossible to account for this comparatively sudden appearance of so highly-organized a vegetation by evolution, unless we admit that there have been periods of rapid evolution, as explained on page 314. When all the conditions are favorable for a great advance, the advance takes place at once, i. e., with great comparative rapidity.

3. We have seen that the coal vegetation is to a large extent anticipated in the Devonian. So, also, to some extent, were the conditions necessary to the preservation of this vegetation and the formation of coal. In the Devonian, for the first time, we find dark bands between the strata, impregnated with carbonaceous matter. We find, also, thin seams of coal, with under-clays filled with ramifying rootlets, such as we shall find in the coal; in other words, we find ancient dirt-beds, fossil forest-grounds, and fossil peat-bogs. All the phenomena of

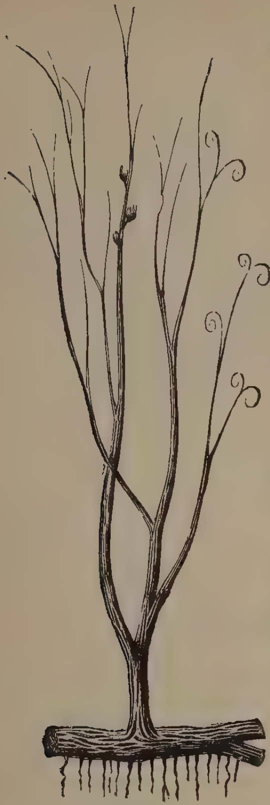
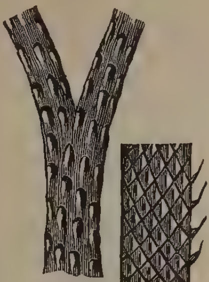
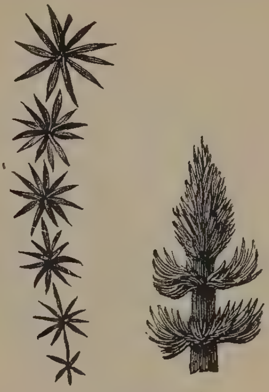


FIG. 395.



a FIG. 396. *b*



a FIG. 397. *b*

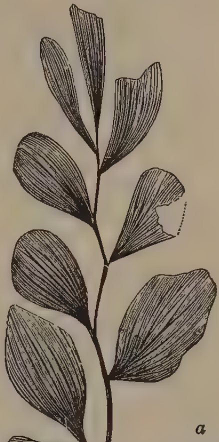


FIG. 398.

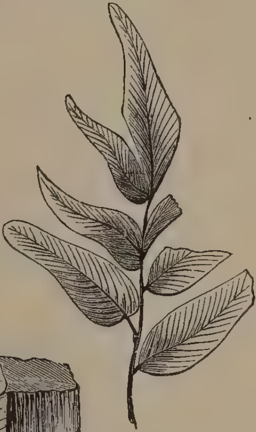
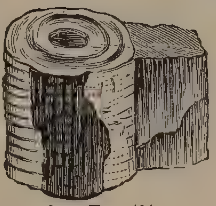
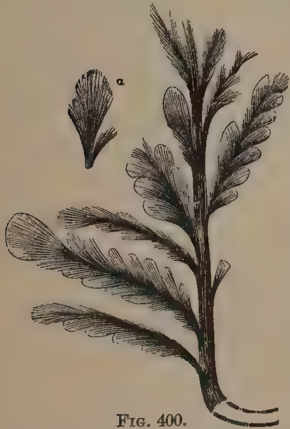


FIG. 399.



b FIG. 401. *c*



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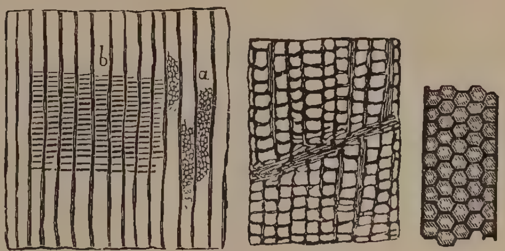
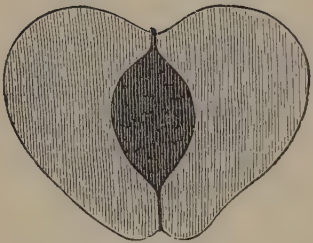


x FIG. 402. *y* *z*

FIGS. 395–402.—DEVONIAN PLANTS (after Dawson): 395. Psilophyton princeps, restored. 396. *a*, Lepidodendron Gaspianum; *b*, same enlarged. 397. *a*, Asterophillites latifolia; *b*, fruit of same. 398. Cyclopteris obtusa—a Fern. 399. Neuropteris polymorpha, a Fern. 400. Cyclopteris Jacksoni, a Fern. 401. Dadoxylon Ouangondianum, a Conifer: *a*, Pith; *b*, Pith-sheath; *c*, Wood. 402. Sections of same: *x*, Longitudinal; *y*, Transverse, enlarged—*z*, greatly magnified, showing disk-like markings.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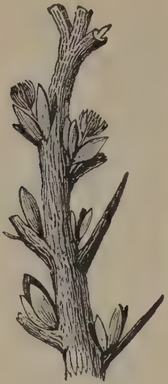
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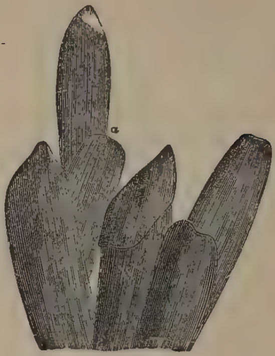
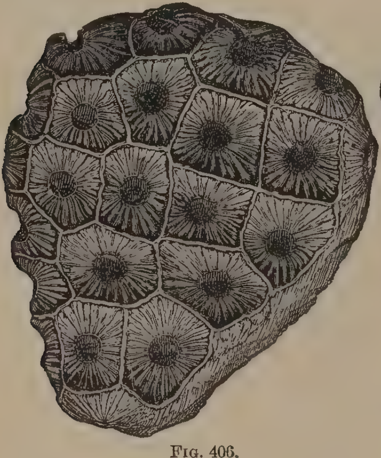


FIG. 405.

FIGS. 403–405.—DEVONIAN PLANTS (after Dawson): 403. Cardiocarpum Baileyi, a Fruit. 404. Anthophyllites Devonicus. 405. Cordaites Robbii, a Group of Leaves.

the coal-measures, therefore, are here found, though imperfectly developed, and the coal not workable. The Carboniferous day is already dawning.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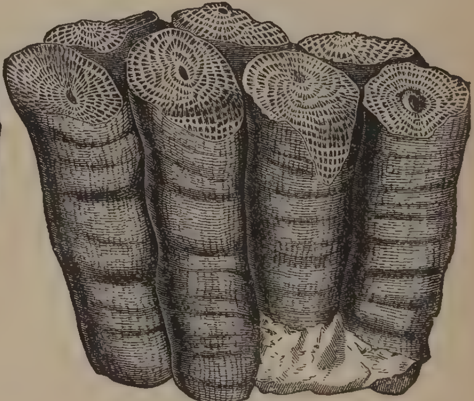
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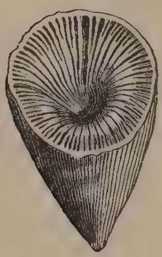
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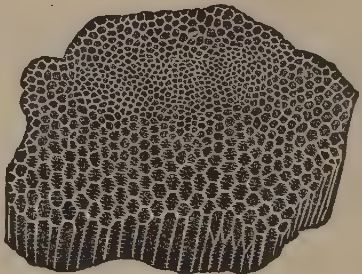


FIG. 409.

FIGS. 406–409.—DEVONIAN CORALS: 406. Acervularia Davidsoni (after Hall). 407. Diphyphyllum Archiaci. 408. Zaphrentis Wortheni (after Meek). 409. Favosites hemispherica.

Animals.

In accordance with our prescribed plan, all we can do in describing Devonian animals is to touch prominent points—to notice what is *going out*, *what is coming in*, some few characteristic forms, and to dwell only on what bears on evolution.

Celenterates.—Among corals, the chain-corals (*Halysitids*) have disappeared; the other orders continue under different species (Figs. 406–409). Among Hydrozoa, the *Graptolites* are gone.

Echinoderms.—Among Crinoids, the *Cystids* are gone, but in their place the *Blastoids* (bud-like), those curious crinoids, with petalloid markings already spoken of as rare in the Silurian, become more abundant. The *Crinids*, or plumose-armed crinoids, continue undiminished. The Blastoids, however, are still more characteristic of the Carboniferous. We therefore defer their illustration to that period.

Brachiopods.—Brachiopods are still very abundant, and still many of them of the characteristic Palæozoic, square-shouldered type. Among spirifers, the long-winged species (Fig. 412) are very abundant and characteristic. We give a few figures of Devonian bivalves, both brachiopods and lamellibranchs, and a few univalves.

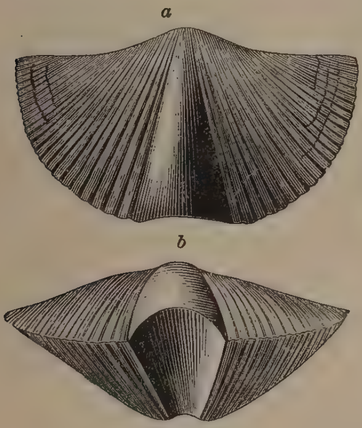


Fig. 410.

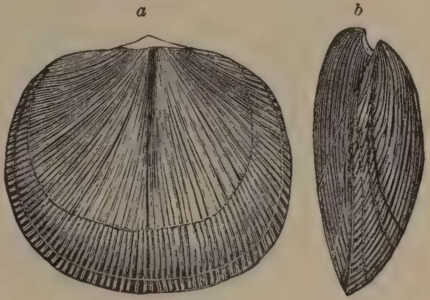
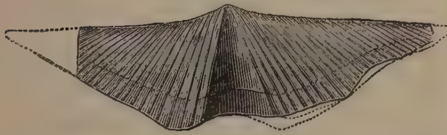


Fig. 411.



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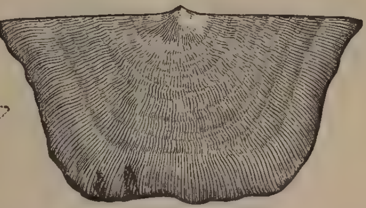


Fig. 413.

Figs. 410–413.—Devonian Brachiopods: 410. Spirifer fornacula (after Meek and Worthen): *a*, Ventral valve; *b*, Front view. 411. Orthis Livia: *a*, Dorsal; *b*, Side view. 412. Spirifer perextensus (after Meek). 413. Strophomena rhomboidalis.

Cephalopods.—The characteristic Palæozoic Cephalopods, or *Orthoceratites*, continue, but in greatly-diminished numbers and size; but the *Goniatites*, a coiled-chambered shell, which seems to be the *beginning of the Ammonite family*, are introduced first here.* This family, as already explained, is distinguished by the complexity of the junction of the septa and the shell (*suture*), and by the ventral position of the siphuncle. In the *Goniatites* the sutures are not yet very complex. They are only *zigzag*. This is shown in the figure.

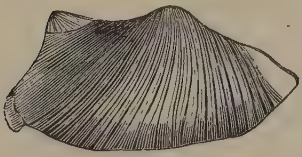
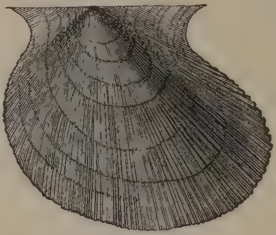


Fig. 414.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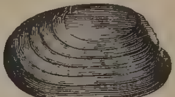
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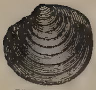
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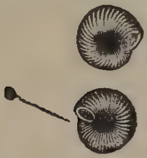
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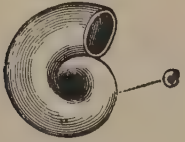
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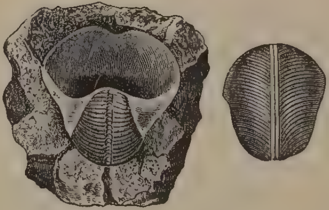
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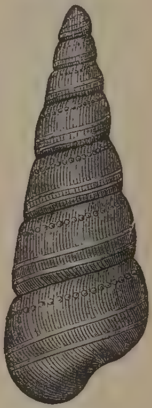
Fig. 420.

Figs. 414–421.—Devonian Lamellibranchs, Gasteropods, and Annelids: 414. Conocardium trigonale (after Logan). 415. Aviculopecten parilis (after Meek). 416. Ctenopistha antiqua (after Meek). 417. Lucina Ohioensis (after Meek). 418. Spirorbis omphalodes, enlarged, a shelled annelid. 419. Spirorbis Arkanensis. 420. Orthonema Newberryi (after Meek). 421. Bellerophon Newberryi (after Meek).

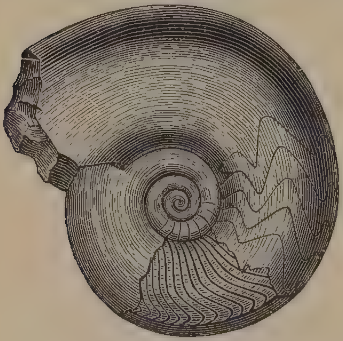
Fig. 422.—Goniatites lamellosus (after Pictet).

Crustacea. — The very characteristic Palæozoic order *Trilobites* is still abundantly represented, although it has already passed its prime, and is diminishing in number and size of species. The *Eurypterids* introduced in the Upper Silurian maintain their place through the Devonian.

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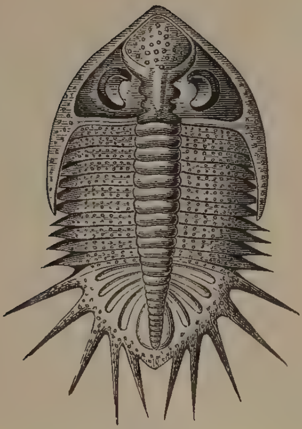
* Some are found in uppermost Silurian in Europe, but not in America.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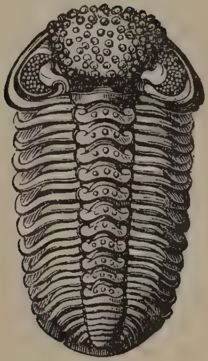
FIG. 424.

FIGS. 423 and 424.—DEVONIAN TRILOBITES: 423. Dalmania punctata, Europe. 424. Phacops latifrons, Europe.

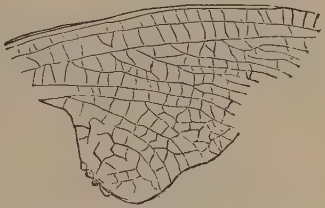
FIG. 425.—Wing of Platephemera antiqua. Devonian, America (after Dawson).

Insects.—We have already seen (page 339) that a very few insects (cockroaches and scorpions) have been found in the Upper Silurian. We treated these as anticipations. In the Devonian, for the first time, they become somewhat abundant; and, as was to be expected, are found in connection with the abundant land vegetation of that time (Figs. 425 and 426).

The Devonian, and, indeed, all the Palæozoic hexapod insects, according to Scudder, belong to one order, Palæodictyoptera (old netted-winged), a generalized type connecting the Neuropters and the Orthopters. A chirping organ is believed to have been found in some. If so, it implies also an *organ of hearing* in these early insects. The supposed chirping organ is shown in Fig. 426.

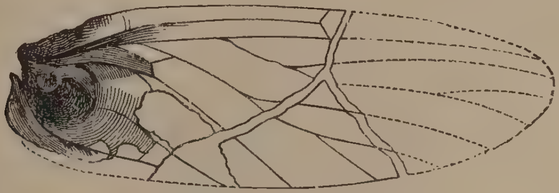
FIG. 426.—Xenoneura antiquorum (after Scudder).

Fishes.—The grand characteristic of the Devonian is the introduction here of a new dominant class—Fishes—and of a new department, and that the highest, to which man himself belongs—the Vertebrates. This is, indeed, a great step in the progress of life. It is necessary, therefore, to treat these somewhat fully.

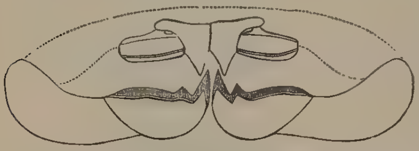

Fig. 427.—Jaws of Dinichthys Terrelli, × $\frac{1}{20}$ (after Newberry).

Commencing far back in the Upper Silurian, few in number, small in size, and of strange unfishlike forms (see Fig. 390, p. 339), with the opening of the Devonian fishes greatly increased in size and number, until the waters fairly swarmed with them. Never since have fishes apparently been more abundant, of greater size, or better armed for offense, and especially for defense. And yet all the species, genera, and even families then existent, are now extinct. Not only so, but *typical* fishes—*Teleosts*—did not then exist. The Devonian fishes were all *Ganoids* and *Elasmobranch* (sharks), especially Ganoids.

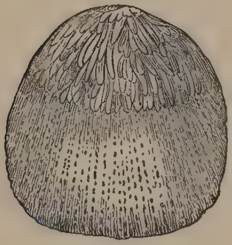

Fig. 428.

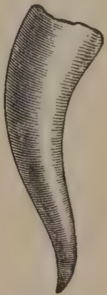

Fig. 429.

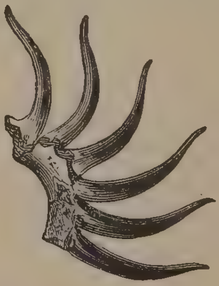

Fig. 430.

Figs. 428–430.—Onychodus sigmoides (after Newberry): 428. Scale, natural size. 429. A Tooth, natural size. 430. A Row of Front Teeth, reduced.

We have said some were of great size. The Dinichthys (Fig. 427) of the Ohio Devonian, according to Newberry, was at least eighteen feet long and three feet thick. A specimen of Titanichthys recently found was nearly six feet across the head (Claypole), and with orbits of eyes three inches in diameter. The animal could hardly have been less than thirty feet long. The Onychodus (Figs. 428–430) was twelve to fifteen feet in length, and had jaws two feet long, armed with teeth two inches long. We have said also that they were many of them armed, especially for defense. All Ganoids, but especially Devonian Ganoids, were covered with an impenetrable coat of mail, composed of thick, closely-fitting, bony, enameled scales or plates. We are indebted to this fact that their external forms are often so well preserved; for their skeletons were wholly cartilaginous, and therefore unsuitable for preservation. The Elasmobranchs, on the other hand, had neither bony skeleton nor bony scales. We know them, therefore, mainly by their teeth and by certain spines supporting their fins, although recently the form of some have been seen. The Ganoids are, therefore, the more interesting.

Characteristic Examples of Devonian Fishes.—The Cephalaspis (Fig. 431) and Pteraspis (Fig. 432) are among the earliest and most curious forms. The former was a small fish, seven or eight inches

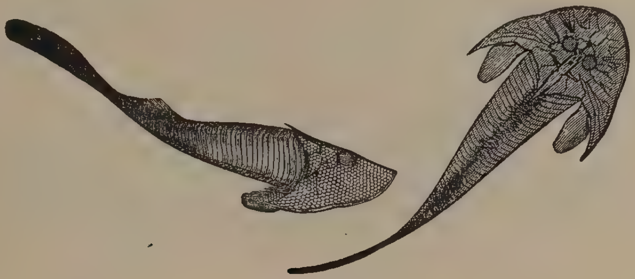

Fig. 431.

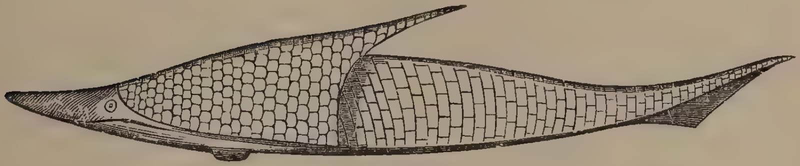

Fig. 432.

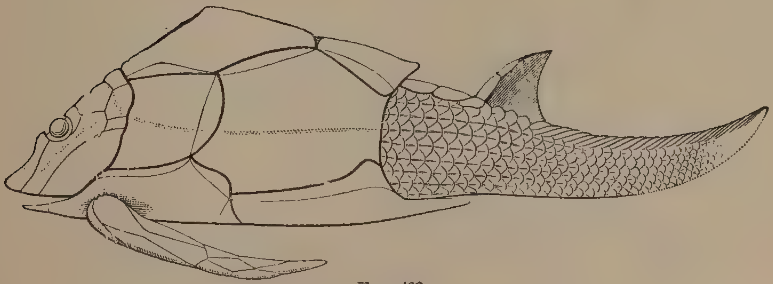

Fig. 433.

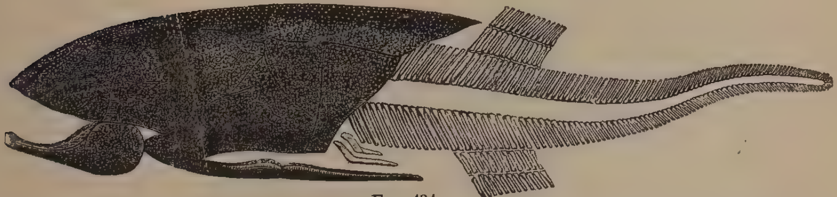

Fig. 434.

Figs. 431.-434.—Devonian Fishes—*Ganoids;* 431. Cephalaspis Lyelli (after Nicholson). 432. Pteraspis restored by Powrie and Lankaster (after Dawson). 433. Pterychthys restored (after Traquair). 434. Coccosteus decipiens (after Owen).

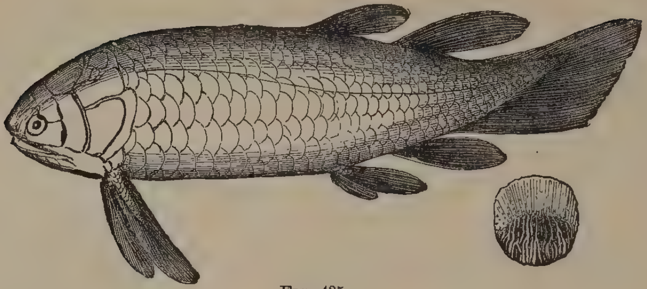

FIG. 435.

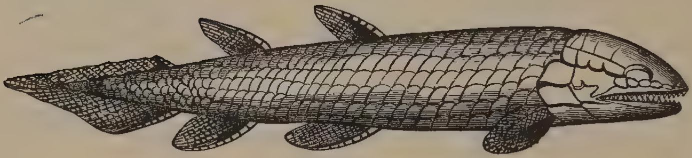

FIG. 436.

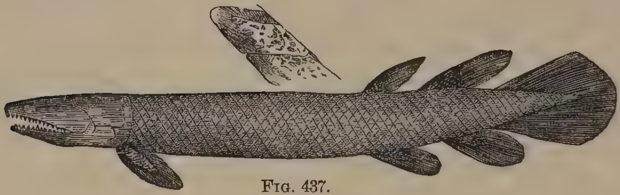

FIG. 437.

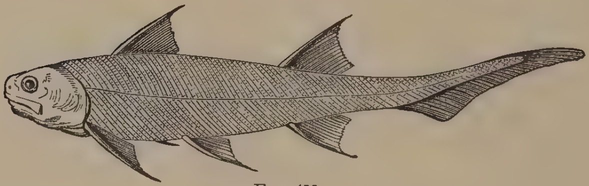

FIG. 438.

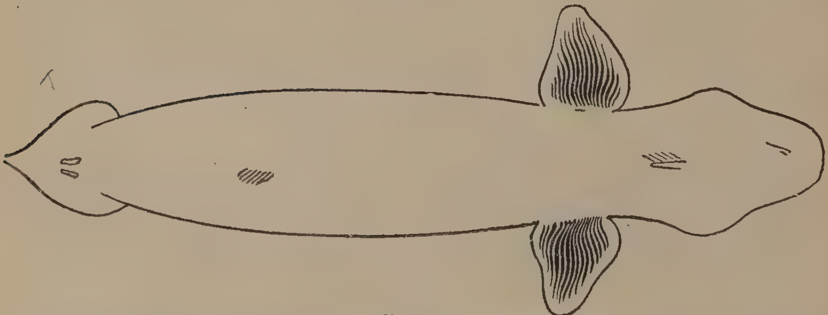

FIG. 439.

FIGS. 435–439.—DEVONIAN FISHES—*Ganoids:* 435. Holoptychius nobilissimus (after Nicholson). 436. Osteolepis (after Nicholson). 437. Glyptolemus Kinairdii (after Nicholson). 438. Diplacanthus gracilis (after Nicholson). *Elasmobranchs:* 439. Cladodus sinuatus, × $\frac{1}{7}$ (after Claypole).

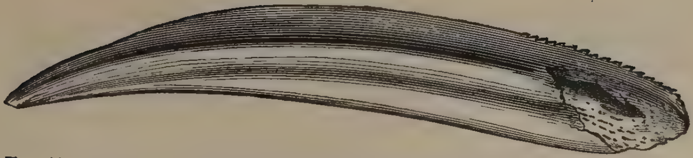

FIG. 440.—DEVONIAN FISH—*Elasmobranchs:* Machæracanthus major, Spine reduced (after Newberry).

long, with a broad head, shaped somewhat like the head-shield of a Trilobite, and covered with bony, enameled plates; and body covered with rhomboidal ganoid scales. In the Coccosteus and Pterichthys (Figs. 433 and 434) the large, close-fitting, immovable plates covered not only the head but the anterior portion of the body. The huge Dinichthys (Fig. 427) and Titanichthys were similarly plated on head and body. Others, however, such as the Osteolepis (Fig. 436), the Holoptychius (Fig. 435), Diplacanthus (Fig. 438), etc., had more fish-like forms, and were covered with movable ganoid scales, either rhomboidal or imbricated.

Perhaps the most extraordinary and certainly the largest of all Devonian fishes belong to the family of Dinichthys. The peculiar structure of jaws and teeth is shown in Fig. 427, taken from Newberry. Almost equally remarkable is another Ohio fish described by Dr. Newberry, the singular teeth of which are shown in Figs. 429 and 430.

Of the Elasmobranchs the external forms are rarely seen. We give an example in Fig. 439, but their teeth and enormous spines are more abundant (Fig. 440).

Classification of Devonian Ganoids.—As above described, Devonian Ganoids fall naturally into two groups—viz., *Lepido-ganoids* (scale Ganoids), or true Ganoids, and *Placo-ganoids* (plate-ganoids), or Placoderms. The *former* are covered, like modern Ganoids, with bony, enameled scales, which may be close-fitting, rhomboidal (Figs. 436–438),

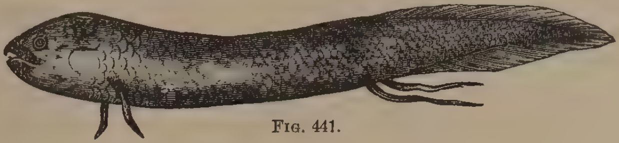

FIG. 441.

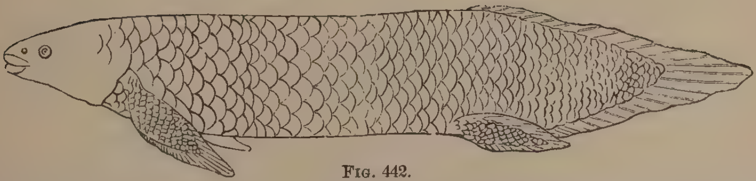

FIG. 442.

FIGS. 441–442.—NEAREST LIVING ALLIES OF DEVONIAN FISHES: 441. Lepidosiren. 442. Ceratodus Fosterii, × $\frac{1}{12}$ (after Gunther).

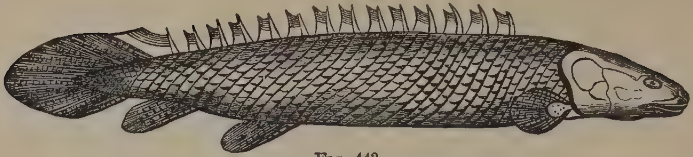

Fig. 443.

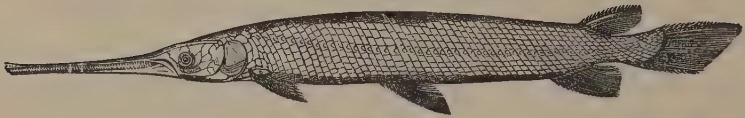

Fig. 444.

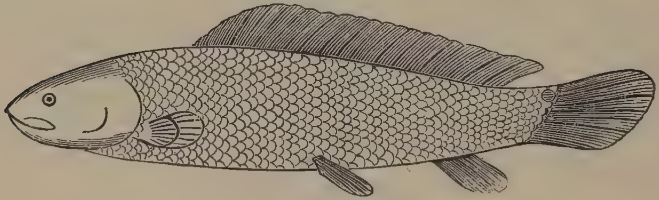

Fig. 445.

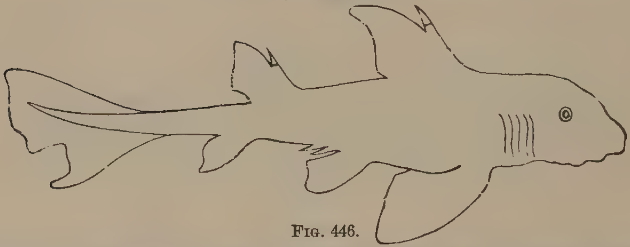

Fig. 446.

Figs. 443–446.—Nearest Living Allies of Devonian Fishes: 443. Polypterus. 444. Lepidosteus (Gar-fish). 445. Amia (American Mud-fish). 446. Cestracion Phillippi (a Living Cestraciont from Australia).

or imbricated (Fig. 435). The *latter* are covered more or less completely with broad, immovable plates (Figs. 433 and 434). The Placoderms are entirely characteristic of the Devonian (and Upper Silurian), and become extinct after that time. The Lepido-ganoids have continued in diminishing numbers and different species, genera, and families, to the present day. One family of these is very characteristic of Devonian—viz., Crossopterygians (fringed-limb), so called because the limbs seem to come out from the body into the fin like a true limb. All the strangest and largest forms—such as the Cephalaspis, the Coccosteus, the Pterichthys, the Dinichthys, and the Titanichthys, are Placoderms. They were heavy, sluggish, uncouth animals, relying for safety rather upon protective armor than upon swiftness.

Nearest Allies among Existing Fishes.—The *Placoderms* have no close allies among living fishes. Some have imagined the sturgeon to be distantly allied; and Dr. Newberry finds some affinities in the Lepidosiren with the Dinichthys. They were probably a generalized type connecting Ganoids and Elasmobranchs. The Lepido-ganoids, however, still have living congeners, which throw light upon their structure (Figs. 441–445). Among the nearest allies are the *Lepidosiren* and Protopterus of South American and African rivers, the *Ceratodus* of Australian rivers, and the *Polypterus* of the Nile. It will be noted that these, especially the first two, have almost veritable legs instead of paired fins. The Ceratodus, especially, is a living Crossopterygian. It is well to note also that the Lepidosiren is the most reptilian or rather amphibian of all fishes, and next in this respect comes Ceratodus. These two have a three-chambered heart and a tolerably good *lung* and nostrils, and breathe air as well as water, like many amphibians. They also have cartilaginous skeletons, like Devonian fishes. Less near allies are found in the gar-fish (Lepidosteus) and the mud-fish (Amia) of our Atlantic and Gulf rivers. These also supplement their gill-breathing with a little air gulped down into their vascular air-bladder from time to time.

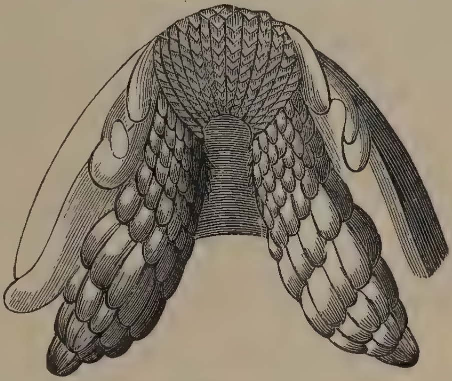

FIG. 447.—Dental Plate of Cestracion Phillippi.

The nearest congener of Devonian Elasmobranchs is found in the *Cestracion*, or Port Jackson shark of Australia (Fig. 446). This is characterized not only by the strong bony spine supporting the median fins, but also by the cobblestone-pavement teeth (Fig. 447) characteristic of Devonian sharks. The family is called *Cestracionts.* The Devonian sharks were nearly all Cestracionts. The Cladodonts alone (Fig. 439) had teeth more nearly approaching those of modern sharks.

General Characteristics of Devonian Fishes.—Leaving out some low aberrant forms, which are so soft and perishable that they are unlikely to be preserved, and therefore are of little geological importance, fishes may be conveniently divided into three orders—viz., Teleosts, Ganoids, and Placoids. Under Ganoids we include also the Dipnoi (Lepidosiren and Ceratodus), because these (Ganoids and Dipnoi), though quite distinct now, run into each other completely in going backward in geological time: 1. Now, of these three orders, the Teleosts (perfect bone) are by far the most numerous at present; so much so, that the word *fish* calls up at once this kind. Under this order come all ordinary or *typical* fishes, such as the perch, the salmon, the cod, etc. In Devonian times, on the contrary, there were no Teleost fishes. *They* *were all Ganoids and Elasmobranchs.* Ganoids are now nearly extinct.

2. Ganoids of the present day have some of them bony skeletons (Lepidosteus), but most of them cartilaginous skeletons. All the Devonian Ganoids had cartilaginous skeletons. Elasmobranchs, both now and in all times, had cartilaginous skeletons. Therefore, all Devonian fishes, without exception, had cartilaginous skeletons. It is well to note that among Teleost fishes this is an embryonic character.

3. The position of the mouth of Teleosts is usually at the end of the snout, or even often looking a little upward. Ganoids now, most of them, have the mouth like Teleosts, at the end of the snout; but some (sturgeon) have it beneath on the ventral surface. The same was true in Devonian times. The Lepido-ganoids had the mouth at end of the snout; but the Placo-ganoids usually on the ventral surface. Elasmobranchs in all times have the mouth beneath. Therefore, all the Devonian fishes, except the Lepido-ganoids, or, we might say, the most characteristic Devonian fishes, have the mouth in the ventral position. This also may be regarded as an embryonic character.

4. The tail-fins of fishes are mainly of two types, the *homocercal* or even-lobed (Fig. 448), and the *heterocercal* or uneven-lobed (Fig. 449). The one is characteristic of Teleosts, the other of sharks and some other fishes. These differ not only in shape, but still more in structure. In the former, the back-bone stops abruptly in a few large joints, which send off the rays to the fin (Fig. 448, B), in the latter the backbone *runs through the fin* and gives off rays in pairs above and below (Fig. 449, B). The former is a *non-vertebrated*, the latter a

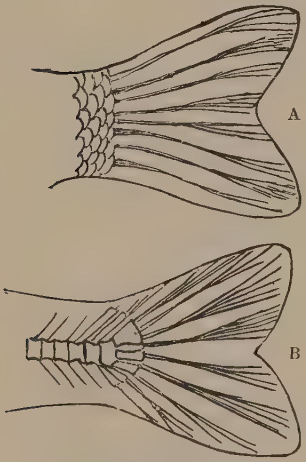

FIG. 448.—Homocercal Tail-fin: A, form; B, structure.

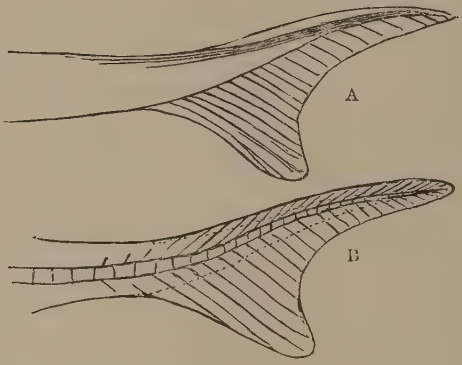

FIG. 449.—Heterocercal or Vertebrated Tail-fin: A, form; B, structure.

vertebrated, tail-fin. There is still a third style in which the tail-fin is *vertebrated* but yet symmetric as in Fig. 450, A and B. This style has been called *diphycercal* by Huxley. It is the most primitive type. It is well to note that in the embryonic development of Teleosts, the tail passes through these stages successively. Now, in living Ganoids, the tail-fin is vertebrated, though in some cases only slightly so; in Devonian Ganoids the tail-fins are always distinctly vertebrated. All Elasmobranchs, both living and extinct, have vertebrated tail-fins. Therefore, *all Devonian fishes, without exception, had vertebrated tail-fins* — sometimes heterocercal (Figs. 432, 435, 438), and sometimes diphycercal (Figs. 433, 436, and 437).

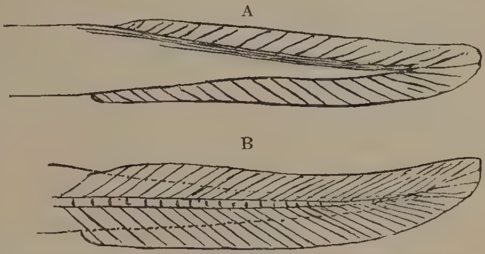

Fig. 450.—Vertebrated but Symmetrical Fin: A, form; B, structure.

5. In all Teleosts, and in nearly all living fishes, the paired fins (corresponding to limbs) are *simply fins*. The bones of the limbs are buried in the body. But there is one very characteristic Devonian family (Crossopterygians) in which the limb is a lobe of the body *running through the fin* and supported by a jointed skeleton. It is more like a paddle or flipper than a true fin. The relation between the two styles of paired fins is similar to that of the two styles of tail-fins. If, in the other case, we had a *vertebrated* tail-fin, in this we have *legged* paired fins. This style of paired fins is still found in some fishes, as the Ceratodus, Fig. 442, and the structure resembling a leg is shown in Figs. 451 and 452.

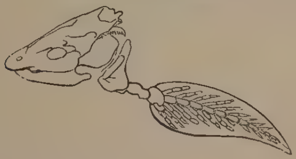

Fig. 451.—Head and fore limb of a Ceratodus.

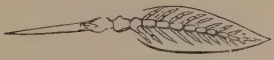

Fig. 452.—Hind-limb of same (after Gunther).

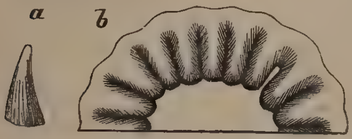

Fig. 453.—Structure of a Ganoid Tooth (after Agassiz): *a*, External form, natural size; *b*, enlarged section, showing structure.

6. The teeth of many Devonian Ganoids are fluted or channeled on the outer surface near the base (Fig. 453, *a*). On section it is found that the inner surface next the pulp is deeply folded (Fig. 453, *b*). This is called *labyrinthine structure*. It is still more marked in early *Amphibians*, and may be regarded as an amphibian character.

7. Devonian Elasmobranchs were nearly all Cestracionts, i. e., they all had cobblestone-pavement teeth, instead of the lancet-shaped teeth characteristic of modern sharks.

Devonian Fishes were Generalized Types.—Teleosts are *typical* fishes; Ganoids and Elasmobranchs, especially Devonian Ganoids and Elasmobranchs, were both *connecting and embryonic* types—i. e., along with their distinctive fish-characters they combined others which connect them with higher vertebrates, especially amphibians, and still others which are found in the embryos of Teleosts. The most important connecting characters of Ganoids, especially Devonian Ganoids, are: 1. An external protective *armor* of thick, bony plates or scales, such as were possessed by early amphibians, and by many reptiles of the present time. 2. Large conical teeth channeled at the base, and of labyrinthine structure on section. This structure was very marked in early amphibians. 3. A cellular air-bladder, freely supplied with blood, opening into the throat, and capable of being used to some extent as a lung. We do not *know* that this was true of Devonian Ganoids, but it probably was, since it is true of all their nearest living allies, viz., Lepidosteus, Polypterus, Amia, and especially Ceratodus and Lepidosiren. 4. In many cases paired fins which had something like jointed legs running through them. 5. The tail-fin vertebrated as in reptiles.

Combined with these connecting characters are others which are distinctly embryonic—i. e., are found now in the embryos of Teleosts. The most conspicuous of these are: 1. Cartilaginous condition of the skeleton, and even the *retention of the fibrous notochord*, which precedes in the embryo the segmentation of the vertebral column. 2. In the Placoderms, the ventral position of the mouth, as in the embryo of Teleosts. 3. The vertebrated tail-fin may be regarded as a *connecting* character, since it is possessed by nearly all amphibians and reptiles. But it may be regarded also as an *embryonic* character, since the tail of a Teleost passes successively through the stages represented by Figs. 448–450, being first diphycercal, then heterocercal, and finally homocercal. It is doubtless both connecting and embryonic.

In Elasmobranchs, both living and extinct, there is a similar combination of connecting and embryonic characters, but in this case the embryonic seem to predominate. We have here, as before: 1. The cartilaginous skeleton. 2. The ventral position of the mouth. But in addition to these, also, 3. The absence of an opercle or gill-cover, growing backward and covering the gill-slits. 4. Perhaps the leathery or imperfectly-rayed condition of the fins; and, 5. The ligamentous instead of bony attachment of the teeth.

On the other hand, the Elasmobranchs, at least those of the present day, have some very high connecting characters in their reproduction.

In all Elasmobranchs the impregnation is *internal* and not external, as is usual in Teleosts; and therefore, instead of spawning a great number of small, unimpregnated ovules, they lay either few large, well-covered, impregnated eggs, like birds and reptiles (skates and some sharks), or else incubate their eggs within the oviduct, and bring forth their young alive (ovo-viviparous) like some reptiles. In some cases there is even an attachment between the yolk-sac of the internally-hatched young and the oviduct of the mother, somewhat similar (but not homologous) to that of the placenta to the uterus in the mammal. The young of Placoids also have, at first, a kind of external branchiæ, like those of amphibians.

The following schedule briefly embodies these facts. It is seen that in the Ganoids the *connecting*, in the Elasmobranchs *embryonic*, characters predominate; but that in the Placoids the connecting characters are very high. The Lepido-ganoids of Devonian and Carboniferous times were far more connecting or reptilian than the Ganoids of the present day. Hence these have been called *Sauroids* by Agassiz and *Herpetichthyes* by Huxley:

Ganoids.		Elasmobranchs.	
Connecting	Bony armor.	Reproduction.	Connecting.
	Teeth labyrinthine.	Tail-fin = vertebrated.	
	Swim-bladder = lungs.	Skeleton = cartilaginous.	Embryonic.
	Paired fins = legged.	Mouth = ventral.	
	Tail-fin = vertebrated.	Gill-slits uncovered.	
Embryonic	Skeleton = cartilaginous.	Fins imperfectly rayed.	
	Mouth = ventral.	Teeth imperfectly attached.	

Bearing of these Facts on the Question of Evolution.—It is seen above that the Devonian fishes combined certain high characters with certain low characters. From one point of view they seem lower, from another higher, than ordinary fishes. There has been some dispute, therefore, whether in the history of fishes we find a law of progress or a law of regress; in other words, whether or not it sustains a law of evolution. The dispute is a result of a misconception of the nature of evolution. The most fundamental law of evolution is the *law of differentiation and specialization*, and the Devonian fishes are an admirable illustration of that law. The law may be stated thus: The first introduced of any class, order, or family, are *not typical* examples of their class, order, etc., but connecting types—i. e., forms which, along with their distinctive classic, ordinal, or family, characters, combine others which connect them with other classes, orders, etc. In the process of evolution such connecting or generalized forms as a common stem are separated into several specialized branches. Thus the Devonian fishes were not typical fishes as we now know them, but *Sauroids*

—i. e., along with their distinctive fish characters they combined others which closely allied them with amphibians. They were the representatives and *progenitors of both classes;* from this common stem diverged two branches, viz., typical fishes on the one hand, and amphibians on the other. Such connecting links with other classes or orders are variously called connecting types, synthetic types, combining types, comprehensive types, generalized types. We shall usually call them *generalized types*, and their differentiated outcomes *specialized types.* We shall find many such in the course of the history of the organic kingdom.

Suddenness of Appearance.—But it is impossible to overlook the apparent suddenness of the appearance of a new class—Fishes—and a new department—Vertebrates—of the animal kingdom. At a certain horizon, and that without break by unconformity, and therefore without notable loss of record, fishes appear in great numbers and variety. It looks at first as if they came without progenitors. This apparent suddenness, however, is greatly diminished by recent discoveries. Fishes, few in number, small in size, and low in organization, have now been found far down in the Upper Silurian. The gap is still great, but will be made less and less by continued discovery. Nevertheless, in spite of all this it is difficult to account for the enormous increase in the number, size, and variety of fishes at the opening of the Devonian unless we admit *paroxysms of more rapid movement* in evolution—unless we admit that, when the conditions are favorable, and the time is ripe for a certain change, it takes place with exceptional rapidity, perhaps in a few generations.

Amphibians and reptiles have not yet been found in the Devonian. Fishes, therefore, were the highest and most powerful animals then living. They were the rulers of the Devonian seas. The previous rulers, therefore—viz., Orthoceratites and Trilobites, according to a necessary law in the struggle for life—diminish in number and size, and seek safety in a subordinate position.

SECTION 3.—CARBONIFEROUS SYSTEM.—AGE OF ACROGENS AND AMPHIBIANS.

Retrospect.—Before taking up in detail this important and interesting age, it will be instructive to glance back over the ground traversed, and draw some conclusions.

If we compare, in physical geography, the American with the European Continent, we find the one marked by *simplicity* and the other by *complexity* of structure. This is true not only of the map-outline, but also of the profile-outline, or orographic structure. Now, as history furnishes the key to social and political structure, so *geology* furnishes the key to physical structure. The American Continent—at least in its eastern part—has developed comparatively *steadily* from the Laurentian nucleus southward and westward, and probably northward. We have already seen how the Silurian area was added to the Laurentian, and the Devonian to the Silurian. It shall be our pleasure, hereafter, to show the continuance of this steady development throughout the whole geological history. For our knowledge on this interesting subject we are indebted almost wholly to Prof. Dana.

In the case of America, the continent thus sketched in outline in the earliest times has been steadily worked out in detail throughout all subsequent time; with some very considerable oscillations, it is true, determining unconformability of strata, rapid changes of physical geography and climate, and therefore of species, thus marking the great divisions of time, but on the whole without change of plan or wavering of purpose; in the case of Europe, on the contrary, geological history consists of a series of oscillations so great that it amounts to a successive making and unmaking of the continent. Therefore Dana has called North America the *type continent* of the world.

Hence, nearly all geological problems are expressed in simpler terms, and are more easily solved, here than there. Hence, also, while in Europe the ages and periods are separated by unconformability of the rock-system, as well as change in the life-system, in America they are separated mainly by change in the life-system only.

Subdivisions of the Carboniferous System and Age.—The Carboniferous age is subdivided into three periods, viz.: 1. Sub-Carboniferous; 2. Coal-measures, or Carboniferous proper; 3. Permian.

The sub-Carboniferous was the period of *preparation;* the Coal-measures the period of *culmination;* the Permian the period of decline and *transition* to the Mesozoic. The whole thickness of the carboniferous strata in Nova Scotia is 16,000 feet; in South Wales it is 14,000 feet; in Pennsylvania 9,000 feet, and in Lancashire 16,336 feet.*

The sub-Carboniferous consists mainly of marine formations; the Coal-measures mainly of fresh-water formation—the former mainly of limestone, the latter mainly of sands and clays; the fossils of the former are, therefore, mainly marine animals, of the latter mainly fresh-water and land animals and plants, though marine animals are also found. In both Europe and America the coal-basins consisting of the latter are underlaid by the former, which, moreover, outcrop all around, forming a penumbral margin to the dark areas representing coal-basins on geological maps (see map, page 302). Between these two, or, rather, forming the lowest member of the Coal-measures, there is, in many places, a thick, coarse sandstone, called the *millstone grit.*

After this general contrast, we will now concentrate nearly our whole attention upon the Carboniferous period proper; because in this middle period culminated all the more striking characteristics of the age. In speaking of the life-system, however, we will draw from both sub-Carboniferous and Carboniferous indifferently. The Permian we shall treat only as a transition to the next *era.*

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* Dawkins, Nature, vol. xxxviii, p. 449, 1888.

Carboniferous Proper—Rock-System or Coal-Measures.

The Name.—The Carboniferous period is but one of the three periods of this age. The Carboniferous age is, again, but one of the three ages of the Palæozoic era, while the Palæozoic era is itself but one of the four great eras, exclusive of the present, of the whole recorded history of the earth. The Carboniferous period, therefore, is probably not more than one thirtieth part of that recorded history. Yet, during that period were accumulated, and in the strata of that period (Coal-measures) are still inclosed, at least nine tenths of all the *worked* coal, and *probably nearly nine tenths of all the workable coal in the world.* It is essentially the *coal-bearing period.* When we remember that every geological period has its characteristic fossils, by means of which the formation may be at once recognized by the experienced eye, it is easy to see the importance of this simple fact as a guide to the prospector. It has been estimated that the money, time, and energy, uselessly expended in the State of New York in explorations for coal, where any geologist might be sure there was no coal, would suffice to make a complete geological survey of the State several times over! The same is true of Great Britain and many other countries.

Thickness of Strata.—Although constituting so small a portion of the whole stratified crust of the earth, the coal-measures are in some places of enormous thickness. In Nova Scotia they are 13,000 feet; in South Wales, 12,000 feet; in Pennsylvania, 4,000 feet; in West Virginia, over 4,500 feet; in Indian Territory, 8,000 to 10,000 feet.*

Mode of Occurrence of Coal.—Such being the thickness of the coal-measures, it is evident that but a small proportion consists of coal. The coal-measures consist, in fact, of thick strata of sandstone, shales, and limestone, like other formations; but in addition to these are interstratified thin seams of *coal* and beds of *iron-ore.* Even in the richest coal-measures, the proportion of coal to rock is not more than as 1 to 50, and the proportion of iron is still much smaller. In some coal-fields, as, for example, in the Appalachian, *mechanical* sediments, shales, and sandstones, predominate; in others, as in the Western coal-fields, *organic* sediments or limestone predominate.

The five kinds of strata mentioned are repeated in the same coal-basin very many times—perhaps 100 or more, as in the accompanying section; but, in comparing one coal-field with another, or in the same coal-field, in comparing one portion of the series with another, there is *no regular order of succession* discoverable. Except that immediately in contact with the seam, and beneath it, there is nearly always a thin stratum of *fine fire-clay.* This constant attendant of a coal-seam is called the *under-clay.* Again, immediately above, and therefore forming the roof of the opened seam, there is frequently, though not so constantly, a shale which, being impregnated with carbonaceous matter, is called the *black shale* or *black slate.* These accompaniments are, however, usually too thin to appear on sections.

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* American Geologist, vol. vi, p. 238, 1890.

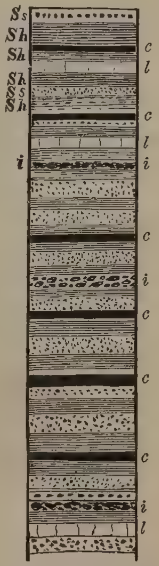

Fig. 454.—Ideal Section, showing Alternation of Different Kinds of Strata: *Ss*, Sandstone; *Sh*, Shale; *l*, Limestone; *i*, Iron; and *c*, Coal.

In different portions, however, of the same coal-field at the same geological horizon, we are apt to find the *same order.* This is the necessary result of the continuity of the strata over the whole basin. If we represent coal-basins, with their five different kinds of strata, by reams of variously-colored paper, then, while the order of succession may be different in the different reams, and in the upper or lower portion of the same ream, yet at the same level we find the same order in every portion of the same ream. This is a test of a coal-field even when separated by denudation into several basins. It is also a mode of identifying individual coal-seams; for, if the strata be continuous, then the seam will have the same accompanying strata above and below. The Pittsburg seam has been thus identified, with great probability, over an area of 14,000 square miles, and, allowing for removal by denudation, over an orignal area of 34,000 square miles. Rogers thinks the original area may have been 90,000 square miles.* This rule for the identification of coal-seams of known value is often of practical importance; but it must be remembered that the strata of coal-measures, both the seams and the accompanying shale and sand-stones, like all other strata, thin out on their edges (page 181). Nevertheless, there is a most extraordinary continuity in the strata of the coal-measures.

Plication and Denudation.—Coal-bearing strata, like all other strata, were, of course, originally horizontal (page 181) and continuous, but, like other strata, they are now found sometimes horizontal and sometimes dipping at all angles, and folded in the most complex manner. In the Appalachian region, especially in the anthracite region of Northern Pennsylvania, the strata are very much disturbed and the coal-seams interstratified with them are often nearly perpendicular (Fig. 455), while in Illinois and Iowa the coal-strata are nearly or quite horizontal (Fig. 456). But, whether horizontal, or gently folded, or strongly plicated, in all cases denudation has carried away much of the upper portions, leaving them in isolated patches as mountains or basins, as shown in the map of Northern Pennsylvania (Fig. 458) and in the section (Fig. 457).

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* Phillips, Geology, p. 217.

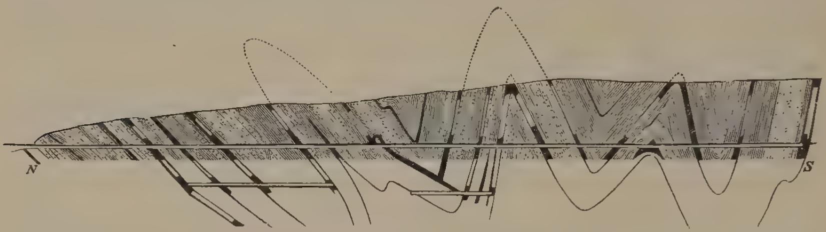

Fig. 455.—Section of Panther Creek Coal-Basin (after Ashburner).

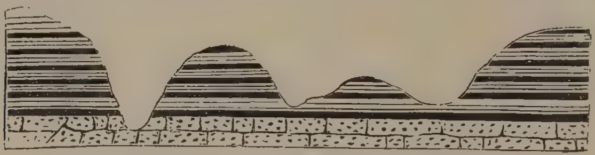

Fig. 456.—Illinois Coal-Field (after Daddow).

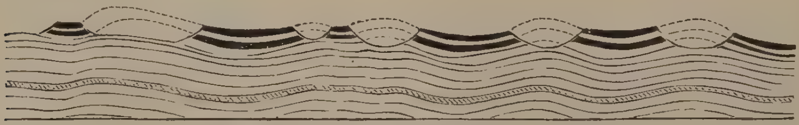

Fig. 457.—Section of Appalachian Coal-Field, Pennsylvania, showing Effects of Erosion on Gently Undulating Strata (after Lesley).

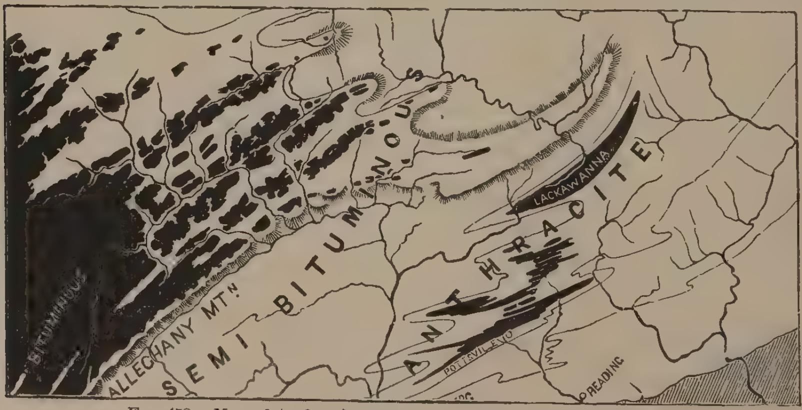

Fig. 458.—Map of Anthracite Region of Pennsylvania (after Lesley),

By means of the rule for identifying seams given above, it is often easy to trace the same seam from one basin to another, or from one mountain-side to another, with great certainty.

Faults.—It is plain, from what has been said above, that there is an essential difference between a coal-*seam* and a metalliferous *vein*. Coal-seams are conformable with the strata, and are therefore *worked wholly between the strata.* This would be a comparatively easy matter if it were not for slips or faults which often occur, and sometimes make the working unprofitable. In case of a fault, it is important to remember the rule already given on page 241, viz., that most commonly the strata on the foot-wall side of the fissure goes upward. In the accompanying section of Yarrow colliery (Fig. 459) it will be seen that all the slips follow this law.

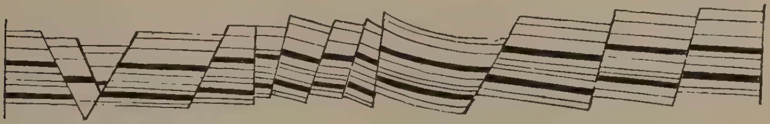

FIG. 459.—Section across Yarrow Colliery, showing the Law of Faults (after De la Beche).

Thickness of Seams.—Coal-seams vary in thickness from a fraction of an inch to forty or fifty feet, or even more. A workable seam must be at least two feet thick. A pure, simple seam is seldom more than eight or ten feet. Mammoth seams, such as occur in the anthracite region of Pennsylvania and in Southern France, are produced by the running together of several seams by the thinning out of the interstratified shales and sandstones. They are, therefore, almost always *compound seams*, i. e., separated by thin partings of clay—too thin to form a good roof or floor, and therefore all worked together.

Number and Aggregate Thickness.—In a single coal-field, we have said, the strata, including the coal-seams, are repeated many times. In the South Joggin's section, Nova Scotia, there are eighty-one coal-seams, though most of these are not workable. In North England there are twenty to thirty seams. In South Wales there are more than 100 seams, seventy of which are worked. In South Lancashire there are seventy-five seams over one foot thick; in Belgium 100 seams, and in Westphalia 117 seams. The *aggregate thickness* of all the seams in Lancashire is 150 feet; in Pottsville, Pennsylvania, 113 feet; in Western coal-fields, 70 feet; in Westphalia, 274 feet; in Mons, 250 feet.*

The thickest and purest are usually near the middle of the series. Evidently the conditions favorable for the formation and preservation of coal commenced gradually, even back in the Devonian, reached their culmination in the middle Coal-measures, and gradually passed away.

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* Nature, vol. xlii, p. 322, 1890.

This geological day had its morning, its high noon, and its evening.

Coal Areas of the United States.—In no other country are the coal-fields so extensive as in the United States. The principal coal-fields are shown on map of Eastern United States, on page 302.

1. *Appalachian Coal-Field.*—This, the greatest coal-field in the world, commences in Northern Pennsylvania, covers the whole of Western Pennsylvania and Eastern Ohio, a large portion of West Virginia and Eastern Kentucky, then passes southward through East Tennessee, touches the northwest corner of Georgia, and ends in Middle Alabama. In general terms, it occupied the western slope of the Appalachian from the confines of New York to Middle Alabama. Its area is at least 60,000 square miles.

2. *Central Coal-Field.*—This covers the larger portion of Illinois, the southwest portion of Indiana, and the western portion of Kentucky. Its area is about 47,000 square miles.

3. *Western Coal-Field.*—This covers the southern portion of Iowa, the northern and western portion of Missouri, the eastern portion of Kansas, and then passes southward through Arkansas, Indian Territory, and into Texas. Its area is estimated at 78,000 square miles. These two coal-fields are seen to be connected by sub-Carboniferous. They are probably one immense field separated by erosion.

4. *Michigan Coal-Field.*—In the very center of the State of Michigan there is another coal-field occupying an area of 6,700 square miles.

5. *Rhode Island Coal-Field.*—A small patch of 500 square miles' area is found in Rhode Island, extending a little into Massachusetts.

6. *Nova Scotia and New Brunswick.*—This is a large area on both sides of the Bay of Fundy. It is estimated at 18,000 square miles.

The following table gives approximately the areas of American coal-fields of the Carboniferous age:

Appalachian	60,000
Central	47,000
Western	78,000
Michigan	6,700
Rhode Island	500
	192,200
Nova Scotia	18,000
	210,000

Of the 190,000 square miles' coal-area of this age in the United States, 120,000 square miles is estimated as workable.

Extra-Carboniferous Coal.—All the fields mentioned above belong to the Carboniferous age. But, besides these, the United States is very rich in coal of other periods. Probably 50,000 square miles might be added from strata of later times, making in all 170,000 square miles of workable coal. But of these latter fields we will speak in their proper places.

Coal-Areas of Different Countries compared.—The following table, taken principally from Dana, exhibits the comparative coal-areas of the principal coal-producing countries of the world:

United States	120,000 to 150,000	square miles.
British America	18,000	"
Great Britain	12,000	"
Spain	4,000	"
France	2,000	"
Germany	1,800	"
Belgium	518	"
Europe, estimated	100,000	"

Recently enormous areas of coal have been found in China, much of which belongs to this age.

Relative Production of Coal.—But if the extent of coal-*area* represents approximately the amount of wealth of this kind present in the strata, the *production* of coal represents how much of this wealth is *active capital;* it represents the development of those *industries dependent on coal.* The following table is compiled from the best sources at hand:

ANNUAL COAL-PRODUCTION IN MILLIONS OF TONS.	1845.	1864.	1874.	1884.	1894.
Great Britain	31·5	90	125	160	164
United States	4·5	22	50	106	152
Germany	....	..	46	70	94
France	4·1	10	17	20	26
Belgium	4·9	10	15	18	19
World	....	..	...	406	566

Inspection of the table shows that in the principal coal-producing countries there is a rapid *increase* of production. It is believed that, if the same rate of increase continues, the annual production of Great Britain will be in thirty years 250,000,000 tons, and the whole workable coal will be exhausted in 110 years.[*] As might be expected, therefore, British statesmen and scientists are casting about with much anxiety for means by which to promote the more economic use of coal. Fortunately, our own country is supplied with almost inexhaustible stores of this source of industrial prosperity.

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[*] Armstrong, Nature, vol. vii, p. 291.

Origin of Coal, and of its Varieties.

That coal is of vegetable origin is now no longer doubtful. We will only briefly enumerate the evidences on which is based the present scientific unanimity on this subject:

1. The remains of an extinct vegetation are found in abundance in immediate connection with coal-seams; stumps and roots in the under-clay, and leaves and stems in the black slate in contact with the seam and even imbedded in the seam itself. 2. These vegetable remains are not only associated with the coal-seam, but have often themselves become coal, though still retaining their original form and structure. 3. Not only these easily-recognizable *imbedded* vegetable fragments, but the *imbedding* substance also, the whole coal-seam, even the most structureless portions, and the hardest varieties, such as anthracite, when carefully prepared in a suitable manner and examined with the microscope, show vegetable structure. Even the ashes of coal, carefully examined, show vegetable cells with characteristic markings. The following figures show the results of such examination. 4. A perfect gradation may be traced from wood or peat, on the one hand, through brown coal, lignite, bituminous coal, to the most structureless anthracite and graphite, on the other, showing that these are all different terms of the same series. In chemical composition, too, the same unbroken series may be traced. 5. Lastly, the best and most structureless peat, by hydraulic pressure, may be made into a substance having many of the qualities and uses of coal.

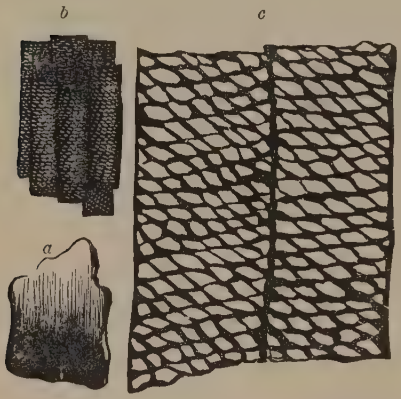

FIG. 460.—Section of Anthracite: *a*, natural size; *b* and *c*, magnified (after Bailey).

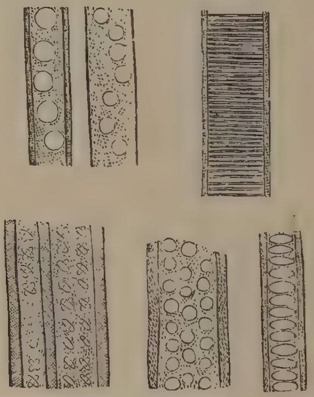

FIG. 461.—Vegetable Structure in Coal (after Dawson).

We may, with perhaps less confidence, go further, and say that all the carbon and hydrocarbon known to us are probably of organic origin. Carbon probably existed at first only as carbonic acid, and has been reduced from that condition only by organic agency.

Varieties of Coal.—The varieties of coal depend upon the *purity*, upon *the degree of bituminization*, and upon the *proportion of fixed and volatile matter.*

Varieties depending upon Purity.—Coal consists partly of organic or combustible and partly of inorganic or incombustible matter. On burning coal, the organic, combustible matter is consumed, and passes away in the form of gas, while the inorganic, incombustible is left as *ash.* Now, the relative proportion of these may vary to any extent. We may have a coal of only one or two per cent ash. We may have a coal of five, ten, fifteen, twenty per cent ash; the coal is now becoming poor. We may have a coal of thirty or forty per cent ash; this is called *bony coal*, or shaly coal; it is the valueless refuse of the mines. We may have a coal of fifty or sixty per cent ash; but it now loses the name as well as the ready combustibility of coal, and is called *coaly shale.* Finally, we may have a coal of seventy, eighty, ninety, ninety-five per cent ash; and thus it passes, by insensible degrees, through black shale into perfect shale. This passage is often observed in the roof of a coal-seam.

Now, all vegetable tissue contains incombustible matter, which, on burning, is left as ash. The amount of ash in vegetable matter is on an average about one to two per cent. But, as in the process of change from wood to coal, much of the organic matter is lost (p. 369 *et seq.*), and the relative amount of ash is thereby increased, we may say that, if a coal contains five per cent or less of ash, it is absolutely pure—i. e., its ash comes wholly from the plants of which it is composed; but if a coal contains more than ten per cent ash, it is probably impure—i. e., mixed with mud at the time of its accumulation.

Varieties of Coal depending on the Degree of Bituminization.—The previously-mentioned varieties consist of *pure* and *impure* coals; these consist of *perfect* and *imperfect* coals. We find the vegetable matter, accumulated in different geological periods, in different stages of that peculiar change called bituminization. Brown coal and lignite are examples of such imperfect coal. They are always comparatively modern.

Varieties depending upon the Proportion of Fixed and Volatile Matter.—Coal, even when pure and perfectly bituminized, consists still of many varieties, having different uses, depending upon the proportion of fixed and volatile matters. These are the *true* varieties of coal.

In pure and perfect coal, then, the combustible matter is part fixed and part volatile. These may be easily separated by heating to redness in a retort. By this means the *volatile* matter is all driven off and may be collected as tar, oil, etc., in condensers, and as permanent gases in gasometers; and the *fixed* matter is left in the retort as coke.

Now, the proportion of these may vary greatly in different coals, and affect the uses to which the coal is applied. For example, when the coal consists wholly of fixed carbon, it is called *graphite.* This is not usually considered a variety of coal, because it is not readily combustible; but it is evidently only *the last term of the coal series.* Its soft, greasy feel, its metallic luster and incombustibility, and its uses for pencils, as a friction-powder, and as a material for crucibles, are well known.

When the combustible matter of the coal contains ninety to ninety-five per cent fixed carbon, it is called *anthracite.* This is a hard, brilliant variety, with conchoidal fracture and high specific gravity. It burns with almost no flame and produces much heat. It is an admirable coal for all household purposes, and, with hot blast, may be used in iron-smelting furnaces.

If the combustible matter contains eighty to eighty-five per cent fixed carbon, and fifteen to twenty per cent volatile matter, it becomes semi-anthracite, or semi-bituminous coal, of various grades. These are free-burning, rapid-burning coals, producing long flame and high temperature, because they do not cake and clog. They are admirably adapted for many purposes, but especially for the rapid production of steam, and therefore for locomotive-engines, and hence are often called *steam-coals.*

If the volatile combustible matter rises to the proportion of thirty to forty per cent, it becomes full bituminous coals, which always burn with a strong bright flame, and often *cake* and form clinkers. This is perhaps the commonest form of coal, and may be regarded as *typical* coal.

If the volatile matter approaches or exceeds fifty per cent, then it forms *highly bituminous* or *fat* or *fusing* coals. This variety is especially adapted to the manufacture of gas and of coke.

Besides these there are several varieties depending on physical character. Thus cannel or parrot coal is a dense, dry, structureless, lusterless, highly-bituminous variety, which breaks with a conchoidal fracture. There may be also some varieties depending upon the kind of plants of which coal was made, but of this we have no certain evidence.

Origin of these Varieties.—There can be little doubt that these, the true varieties, are produced by slight differences in the nature and degree of chemical change in the process of bituminization.

It will be seen by the following table, giving approximate formulæ, that vegetable matter and coal of various grades have the same general composition, except that in the latter case some of the carbon and much of the hydrogen and oxygen have passed away in the process of change:

Vegetable matter, cellulose	$C_{36}H_{60}O_{30}$
Bituminous coal	$C_{26}H_{10}O_2$
Anthracite "	$C_{40}H_8O$
Graphite "	C pure

The gradual loss of the hydrogen and oxygen is still better shown in the following table, in which the constituents are given in proportionate weights instead of equivalents, and the carbon reduced to a constant quantity:

KINDS OF VEGETABLE MATTER AND COALS.	Carbon.	Hydrogen.	Oxygen.
Cellulose	100·00	16·66	133·33
Wood	100·00	12·18	83·07
Peat	100·00	9·83	55·67
Lignite	100·00	8·37	42·42
Bituminous coal	100·00	6·12	21·23
Anthracite "	100·00	2·84	1·74
Graphite "	100·00	0·00	0·00

Now, there are two modes of decomposition to which vegetable matter may be subjected, viz.: 1. In contact with air; and, 2. Out of contact with air. The first is partly decomposition, and partly oxidation by the air (*eremacausis*); the second is wholly decomposition.

In Contact with Air.—Under these conditions the carbon of the vegetable matter unites with the *oxygen of the vegetable matter*, forming carbonic acid (CO_2); and the hydrogen of the vegetable matter unites with the oxygen of the *air*, forming water (H_2O). Further, it is evident that, for every equivalent of carbon thus lost, there are two equivalents of oxygen and four equivalents of hydrogen lost, so as always to maintain the same relative proportion of H, and O viz., the proportion forming water (H_2O). The final result of this process is *pure carbon.* It is very improbable, however, that anthracite or graphite is formed in this way; for vegetable matter, by aërial decay, falls to powder. It is very probable, however—nay, almost certain—that a peculiar substance, pulverulent and retaining vegetable structure in a remarkable degree, called *mineral charcoal*, found very commonly in some stratified coals has been formed by partial aërial decay, somewhat as represented in the table. Mineral charcoal has a high percentage of carbon, with very little hydrogen and oxygen.

Cellulose	$C_{36}H_{60}O_{30}$
Decayed	$C_{35}H_{56}O_{28}$
More decayed	$C_{34}H_{52}O_{26}$
Final result	C_{21}

Out of Contact with Air.—When vegetable matter is buried in mud or submerged in water, its *elements react on each other.* Some of the carbon unites with some of the oxygen, forming carbonic acid (CO_2); some of the carbon unites with some of the hydrogen, forming carbureted hydrogen or marsh-gas (CH_4); and some of the hydrogen unites with some of the oxygen, forming water (H_2O). These products are probably formed in all cases of vegetable decomposition under these conditions: If, for example, we stir up the mud at the bottom of stagnant pools where weeds are growing, the bubbles which rise always consist of a mixture of CO_2 and CH_4. In every coal-mine these same gases are constantly given off; the one being the deadly *choke-damp* and the other the terrible *fire-damp* of the miners. Now, by varying the relative amounts of these products, it is easy to see how all the principal varieties of bituminous coal may be formed. I have given below the approximate composition of typical varieties of bituminous coal, and of graphite, and constructed formulæ expressing the chemical change by which they are formed:

Vegetable matter—cellulose		$C_{36}H_{60}O_{30}$*	
Subtract	$9CO_2$ $3CH_4$ $11H_2O$	$C_{12}H_{34}O_{29}$	
And there remain		$C_{24}H_{26}O$	= cannel.
Again, vegetable matter		$C_{36}H_{60}O_{30}$	
Subtract	$7CO_2$ $3CH_4$ $14H_2O$	$C_{10}H_{40}O_{28}$	
And there remain		$C_{26}H_{20}O_2$	= bituminous coal from Staffordshire.
Again, vegetable matter		$C_{36}H_{60}O_{30}$	
Subtract	$10CO_2$ $10CH_4$ $10H_2O$	$C_{20}H_{60}O_{30}$	
And there remains		C_{16}	= graphite.

The composition of vegetable matter varies considerably. The composition of the varieties of coal is differently given by different authorities. Different reactions from those above given might be contrived which would give as good results. These reactions, therefore, are not given as certainly the actual reactions which take place. They are only intended to show the general character of the changes which take place in the formation of coal.

Metamorphic Coal.—It is probable that bituminous coal is the *normal* coal formed by the above process, and that the extreme forms, anthracite and graphite, are the result of an after-change produced by heat. But some geologists go further: they believe that anthracite has been changed by intense heat sufficient to vaporize the volatile matters, which then condense in fissures above, as bitumen, petroleum, etc.; that, as in art, when bituminous coal is subjected to heat out of contact with air, the fixed carbon is left as coke, the tarry and liquid matters are condensed in purifiers, and the permanent gases collected in gasometers; so in Nature, when beds of bituminous coal are subjected to intense heat in the interior of the earth, the fixed carbon is left as *anthracite*, the tarry and liquid matters collected in fissures, as bitumen and petroleum, while the gases escape in burning springs. The process is of course slow and under heavy pressure, and therefore the residuum is not spongy like coke. According to this view, anthracite and bitumen are necessary correlatives.

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* The composition of *wood—timber*—is usually given as about $C_{12}H_{18}O_8$. I have taken the formula of cellulose instead, viz., $C_6H_{10}O_5$; or, taking six equivalents for convenience of calculation, $C_{36}H_{60}O_{30}$. I believe this to be much nearer the composition of vegetable matter of the *Coal period* than is the formula of hard wood like oak or beech. All the results may be worked out, however, with equal ease by the use of either formula for vegetable matter.

There can be no doubt that the graphitic and anthracitic varieties of coal are always associated with folding and metamorphism of the strata: 1. In the universally-folded and metamorphic Archæan rocks only graphite is found. 2. In Pennsylvania, in the strongly-folded and highly-metamorphic eastern portion of the field, the coal is anthracite; while, as we go westward, and the rocks are less and less metamorphic, the coal is more and more bituminous, until, when the rocks are horizontal and unchanged, the coal is always highly bituminous. The same has been observed in Wales: anthracite is always found in metamorphic regions, and the coal is more and more bituminous as the rocks are less and less metamorphic. 3. Again, the anthracitic condition of coal may be sometimes traced to the local effect of trap or volcanic overflows. In a word, anthracite is *metamorphic* coal; and, according to this view, the same heat which changed the rocks has distilled away the volatile matters, which may condense above, as bitumen or petroleum.

We have given above the common view. It is partly true and partly erroneous. The true view seems to be as follows:

Anthracite may, indeed, be regarded as metamorphic coal, but it is not probable that bitumen is its necessary correlative; it is not probable that the heat of metamorphism is sufficient to produce destructive distillation. We have already shown (page 230) that a moderate heat of 300° to 400° Fahr. in the presence of water is sufficient to produce metamorphism. Such a degree of heat would, doubtless, hasten the process explained on page 370. The folding and erosion of the rocks, and the consequent exposure of the edges of the seams, would still further hasten the process, and bring about anthracitism by facilitating the escape of the products of decomposition. In all coal-mines CO_2, CH_4, and H_2O, are eliminated *now;* only continue this process long enough, and anthracite and, finally, graphite is the result. We must conclude, then, that high heat is not necessary to produce anthracitism; for, if it is unnecessary for metamorphism of *rocks*, much less is it necessary for metamorphism of *coal.*

Plants of the Coal—their Structure and Affinities.

The flora of the coal-measures is one of the most abundant and perfect of all extinct floras. According to Ward, there are about 8,660 known fossil species of plants, and of these about 2,000, or nearly one fourth, are from the coal-measures.* This flora is peculiarly interesting to the geologist, not only on account of its relative abundance, but also and chiefly because, being the first diversified and somewhat highly-organized flora, it is natural to suppose that *the great classes and orders of the vegetable kingdom commenced to diverge here;* and therefore it furnishes a key to the evolution of land-plants. We will, therefore, discuss the affinities of these plants somewhat fully.

Where found.—The plants of the Coal are found principally: 1. In the form of *stools and roots* in their orginal position in the *under clay;* 2. Of *leaves*, and *branches*, and *flattened trunks*, on the upper surface of the coal-seam, and in the overlying *shale;* 3. And, finally, in the form of *logs*, apparently drift-timber, in the *sandstones* above the coal-seam. The black shale overlying the seam is often full of leaves and fronds of ferns, and of the flattened trunks of other families, in the most beautiful state of preservation, so that even the finest venation of the leaves is perfectly distinct. In some cases where the shale is light-colored, so as to contrast strongly with the jet-black leaves, the effect on first opening a seam is very striking, and has been compared to the frescoes on the ceilings of Italian palaces.

Principal Orders.—Leaving out some plants of doubtful affinity, the plants of the Coal may be referred to five orders or families, viz., *Conifers*, *Ferns*, *Lepidodendrids*, *Sigillarids*, and *Calamariæ*. It is usual to refer these last three to the two orders Lycopods and Equisetæ; but they are so peculiar, and their affinities still so doubtful, that we have preferred to treat them as distinct orders.

All these, as already seen, commenced in the Devonian, as did also the preservations of their tissues as coal; but both the vegetation and the conditions necessary for their preservation culminated in the Coal period, and therefore we have put off their discussion until now. Contrary to our usual custom, we will commence with the highest, viz.:

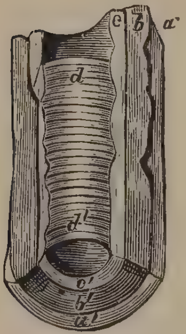

FIG. 462.—Trunk of a Conifer: *a*, bark; *b*, wood; *c*, medullary sheath; *d*, pith.

1. **Conifers.**—A considerable number of genera of these are known, but all of them quite different from

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* Science, vol. iv, p. 340, 1884.

living Conifers. They are mostly found: 1. In the form of trunks or logs in the sandstones above the coal-seams (Fig. 462); 2. In the form of leaves, twigs, and leafy branches in the roof-shale (Fig. 463); 3. In the form of nut-like fruits of many kinds, also in the roof-shale. But they are *not* found as stumps and roots *in situ* in the under-clay. From this we conclude that they did not grow *in* the coal-swamps, but on the high ground *about* them; that their leaves, small branches, and fruits were washed down into the swamps, and their trunks were sometimes drifted down by floods which overwhelmed and buried the coal.

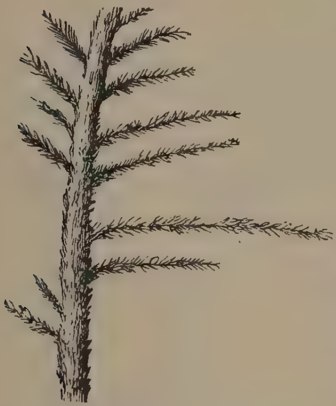

Fig. 463.—Araucarites gracilis, reduced (after Dawson).

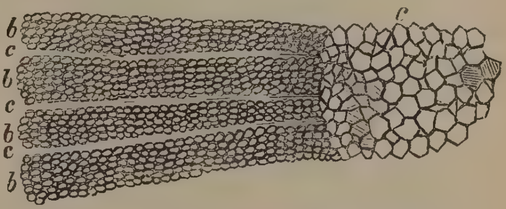

Fig. 464.—Section of same: *b*, woody wedges; *c*, pith and pith-rays.

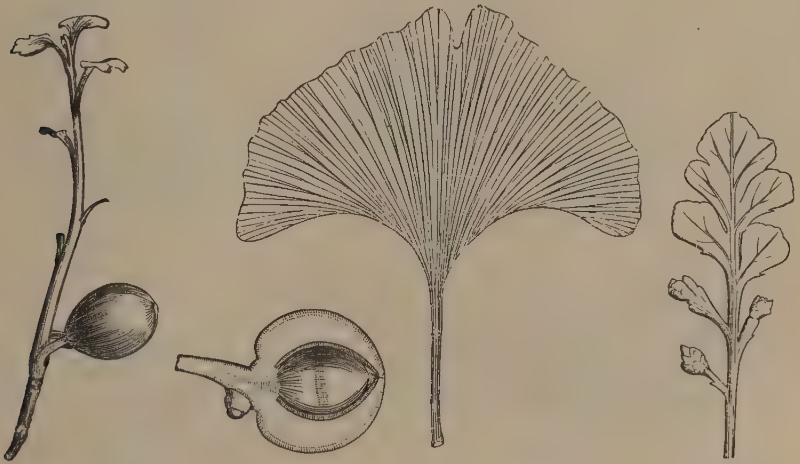

Fig. 465. Fig. 466. Fig. 467. Fig. 468.

Figs. 465-468.—Broad-Leaved Conifers. Living Congeners of some Coal-Plants: 465 Salisburia (Ginkgo), a branch. 466. Section of fruit. 467. A leaf, natural size. 468. Phyllocladus, a branch.

The trunks and woody branches are known to be those of Gymnosperms by the characteristic Gymnospermous structure of the wood (Figs. 392, 393, and 394, page 341), especially the disk-like markings on longitudinal section; and to be those of Conifers by the existence of a distinct bark, rings of growth, and pith (Fig. 462). But the large size of the pith of some seems to ally them with the Cycads.

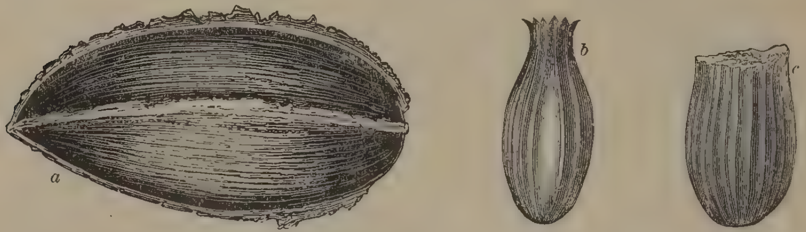

Fig. 469.

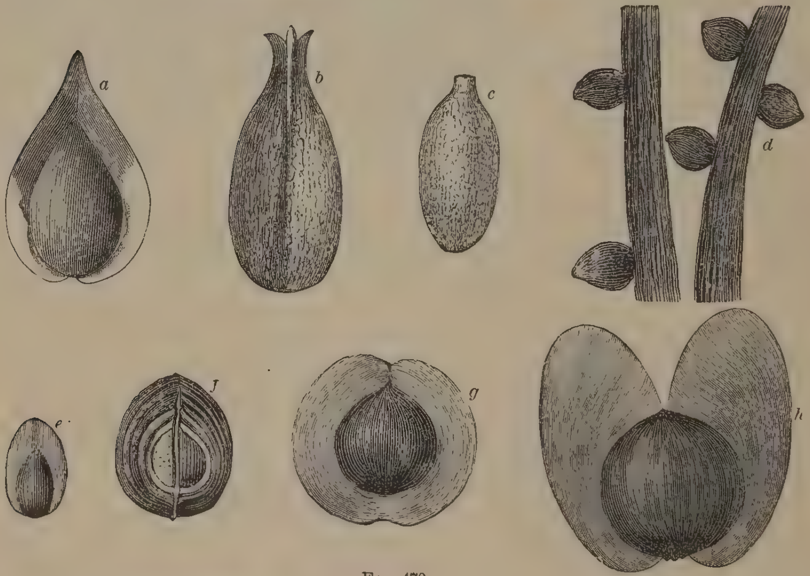

Fig. 470.

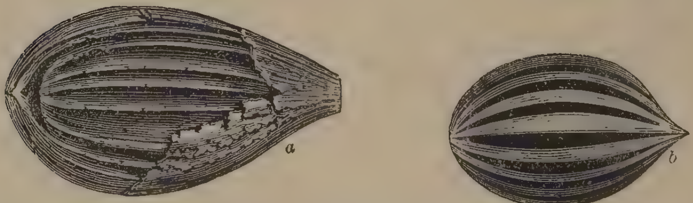

Fig. 471.

Figs. 469–471.—Fruits of Coal-Plants, probably Conifers: 469. Trigonocarpon (after Newberry). 470. Cardiocarpon (after Newberry and Dawson). 471. Rhabdocarpon (after Newberry).

But the leaves, leafy branches, and fruits are still more interesting and significant. By the study of these, Carboniferous Conifers seem to fall naturally into two groups, viz., those with small, spine-like leaves (Fig. 463), reminding us of the yew or the Araucaria, and those with broad, strap-shaped, or tongue-like leaves, with parallel or radiated venation, like that strange, broad-leaved living Conifer, the Ginkgo (Fig. 467). One of the commonest and most characteristic of this group is the *Cordaites.* All parts of this plant are known; so that we may restore it with some confidence (Fig. 472). We may imagine a cylindrical, branchless trunk, sometimes sixty to seventy feet high, clothed atop with long, strap-shaped leaves like a Dracæna, and bearing clusters of nut-like fruits. Many of the fruits represented in the figures on the previous page are from this tree.

Affinities of Carboniferous Conifers.—Conifers of this time were not typical Conifers. There are no signs of true cones in the coal. All the so-called Conifers of that time bore *solitary*, *nut-like* fruits. Now, Conifers of the yew family, and the broad-leaved Ginkgo, are the only ones that now bear fruits which might be compared with these. These Conifers bear solitary plum-like fruits, with large, nut-like seeds (Figs. 465 and 466). The Cycads also bear somewhat similar fruit. The best illustration from the yew family is the California nutmeg (Torreya). It bears a plum-like fruit about the size of a large plum, with a nut-like seed as large as a pecan-nut. It is, therefore, among the yew family and the Ginkgos that we must seek for allies of the coal Conifers. In fact, all gradations in shape of the leaf may be traced between the Cordaites (Fig. 473, *a*, *b*) and Nöggerathia, of the Carboniferous (*c*), and Ginkgophyllum of Permian (*d*) to Ginkgo (*e*, *f*) of the Jurassic, and the present time. The yew family and the Ginkgo may be regarded as the most generalized of Conifers, connecting

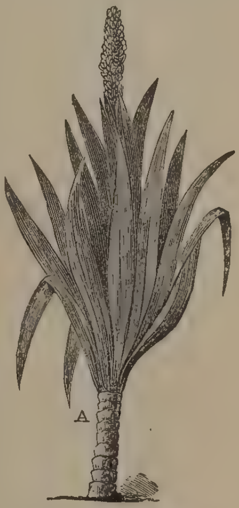

FIG. 472.—Cordaites (restored by Dawson).

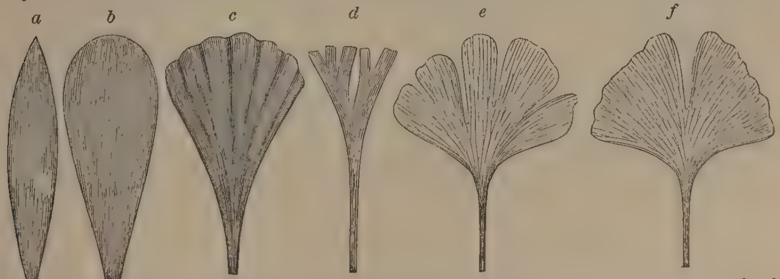

FIG. 473.—Evolution of the Ginkgos: *a* and *b* Cordaites, Carboniferous: *c*, Nöggerathia, Carboniferous; *d*, Ginkgophyllum, Permian; *e*, Ginkgo digatata, Oölite; *f*, Ginkgo biloba, living.

them closely with the Cycads on the one hand, and the vascular Cryptogams on the other. Many writers ally the Cordaites and Nöggerathia with the Cycads instead of the Conifers. They probably connect these two families of Gymnosperms.

2. **Ferns.**—Ferns are the most abundant plants of the Coal period, both as to individuals and as to variety of *species*. About one third to one half of all the known species of coal-plants, both in this country and in Europe, belong to this order. They represent both ordinary forms, i. e., those with creeping stems, and *Tree-ferns*, like those now growing only in warm latitudes (Fig. 474). They are known to be ferns by their large complex fronds (Fig. 475), sometimes six to eight feet long; by the dichotomous venation of their leaves (Fig. 479); and by the position of their organs of fructification (*spore-cases*) on the under-surfaces of the leaves (Figs. 480 and 481). In some localities these spore-cases are so abundant that the coal seems to be almost wholly made up of them. The trunks of Tree-ferns are known by the large, ragged, ovoid marks left by the falling of the fronds (leaf-scars—Figs. 489–491), and by the peculiar arrangement of the *vascular* tissue in the cellular in the cross-section. Some coal Tree-ferns had their large fronds in two vertical ranks (Megaphyton—Fig. 475).

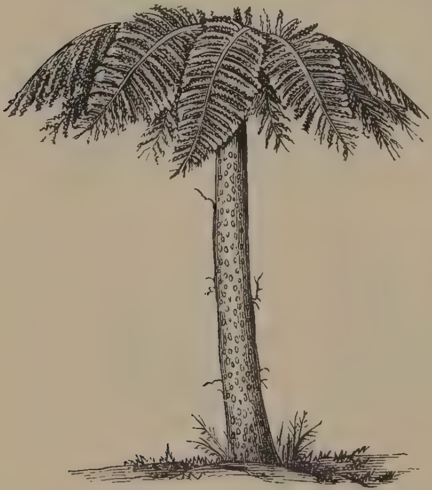

Fig. 474.—Living Tree-Fern.

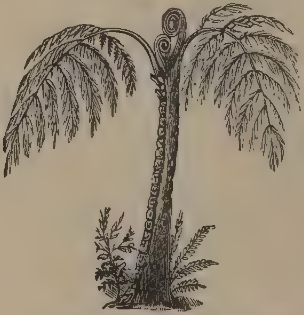

Fig. 475 —Megaphyton, a Coal-Fern restored (after Dawson).

The Ferns of the Coal are, therefore, unmistakably Ferns, yet botanists recognize some features which connect them with other classes. Caruthers thinks that he finds in the internal structure of the stems of Tree-ferns of the Coal two types which are the foreshadowings of the Monocotyls on the one hand, and the Dicotyls on the other; and that therefore they are probably the progenitors, not only of the Tree-ferns of the present day, but also of the Palms and the foliferous Exogens.*

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* Nature, vol. vi, p. 486, and Scott, American Journal, vol. ix, p. 45.

The next three orders we will discuss more fully for two reasons: First, the *Conifers* were probably mostly highland plants, and only found their way into the coal-swamps by accident, being in fact brought down by freshets. The Ferns formed the thick underbrush of the coal-swamps. Neither of these contributed a very large share to the material of the coal-seams. The great trees of the coal-swamps, and which formed the larger part of the material preserved as coal, were *Lepidodendrids*, *Sigillarids*, and *Calamariæ*.

Again, the Conifers and Ferns were unmistakably Conifers and Ferns, though certainly with characters connecting with other orders and classes; but the three orders now about to be discussed combine so completely the characters of widely-separated classes that there is still some doubt as to their real place. For that very reason, however, they are peculiarly interesting to the evolutionist.

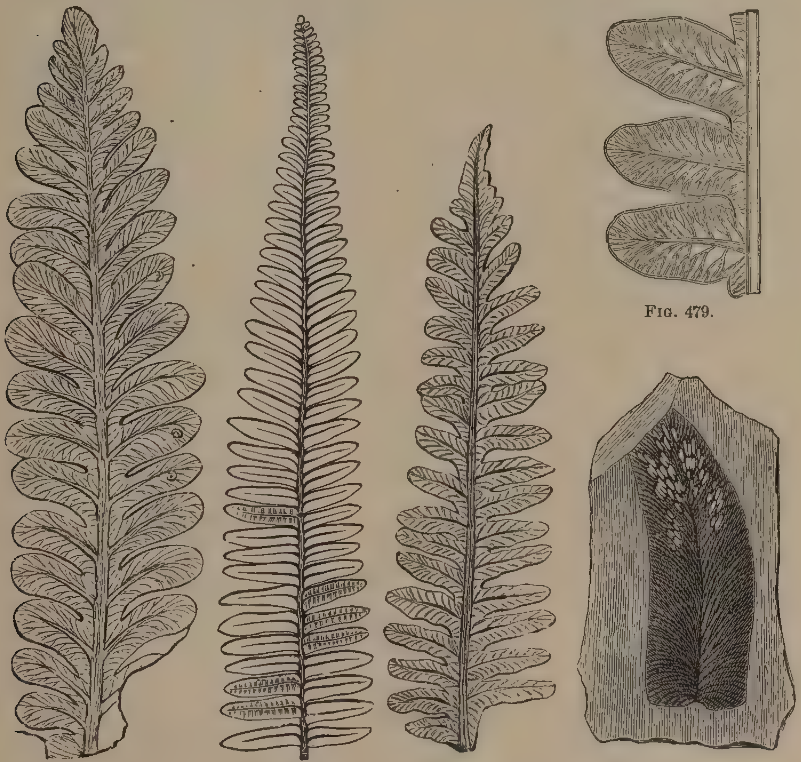


FIG. 476. FIG. 477. FIG. 478. FIG. 479. FIG. 480.

FIGS. 476–480.—COAL-FERNS: 476. Callipteris Sullivanti (after Lesquereux). 477. Pecopteris Strongii (after Lesquereux). 478. Alethopteris Massilonis (after Lesquereux). 479. Same enlarged to show dichotomous venation. 480. Neuropteris flexuosa (after Brongniart).

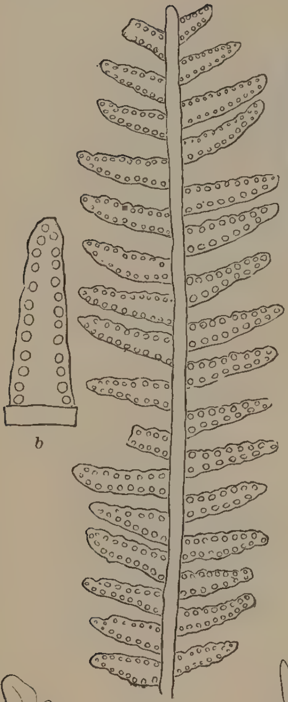


FIG. 481.

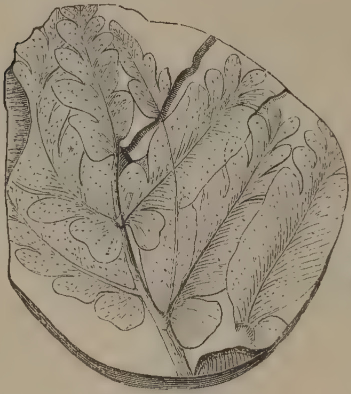


FIG. 482.

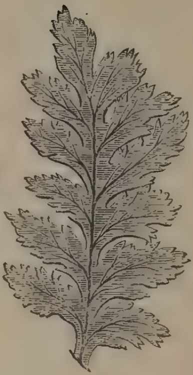


FIG. 483.

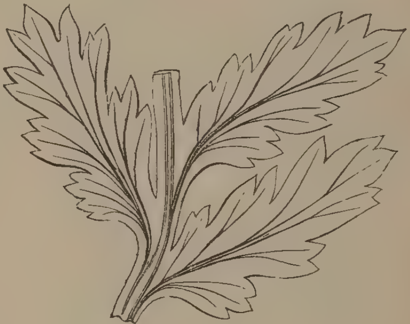
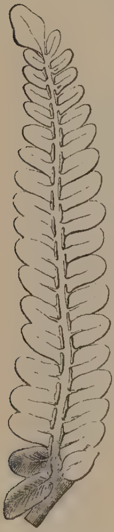


FIG. 488.



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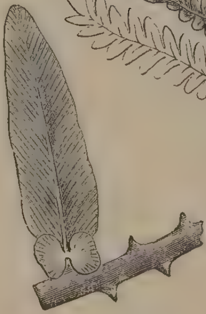

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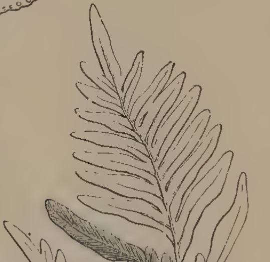

FIG. 486.

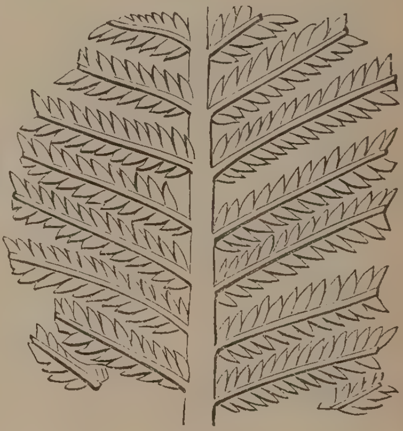

FIG. 487.

FIGS. 481–488.—COAL-FERNS (after Lesquereux): 481. Pecopteris Strongii, showing fructification; *b*, a leaflet enlarged. 482. Odontopteris Wortheni. 483. Hymenophyllites alatus. 484. Neuropteris flexuosa. 485. Neuropteris hirsuta. 486. Alethopteris lonchitica. 487. Odontopteris gracillima (after Newberry). 488. Hymenophyllites splendens (after Lesquereux).

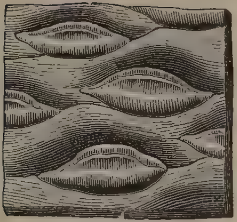

FIG. 489.

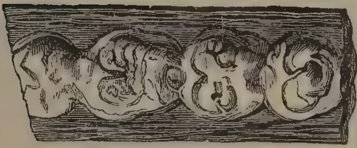

FIG. 490.

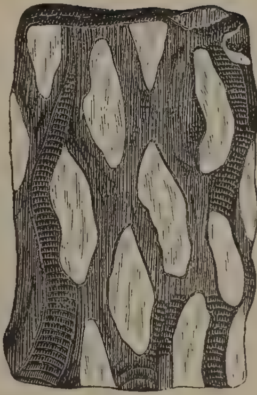

FIG. 491.

FIGS. 489-491.—COAL-FERNS: 489. Leaf-Scars of Palæopteris, × ½ (after Dawson). 490. Leaf-Scar of Megaphyton, × ⅛ (after Dawson). 491. Caulopteris primeva, showing Leaf-Scars.

3. **Lepidodendrids.**—These are so called from the typical genus *Lepidodendron.* We will describe only this genus.

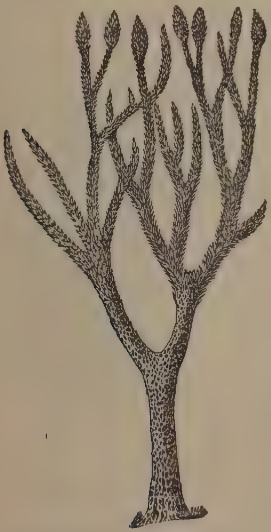

FIG. 492.—Restoration of a Lepidodendron, by Dawson.

Lepidodendrons are found most commonly in flattened masses representing portions of the trunk or branches, very regularly marked in rhomboidal pattern, and much resembling the impression of the scaly surface of a Ganoid fish. The name Lepidodendron (scale-tree) is derived from this fact (Figs. 493 to 495). These marks are the scars of the regularly-arranged and crowded leaves. All portions of the plant, however, viz., the roots, the trunk, the branches, the leaves, and the fruit, have been found in abundance. From these the general appearance of the tree has been approximately reconstructed. Imagine, then, a tree two to four feet in diameter at base, forty to sixty feet high, with wide-spreading *roots*, well adapted for support on a swampy soil; the *surface* of the trunk and branches regularly marked in rhomboidal pattern, representing the phyllotaxis; the *trunk* dividing and subdividing, but not profusely, into branches which are thickly clothed with scale-like, or spine-like, or needle-like leaves (Figs. 496 and 498), and terminated by a club-shaped extremity (Figs. 497, 499, and 500) like the terminal cones of some conifers, or still more like the club-shaped extremities of club-moss branches—and we will have a tolerably correct idea of the Lepidodendron.

The general appearance of the tree is that of an Araucarian conifer, or of a gigantic club-moss. The fruit, however, turns the scale of affinity in favor of the club-moss; for the examination of these, which are

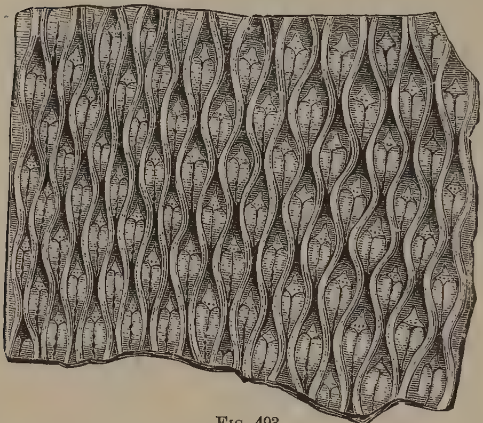

FIG. 493.

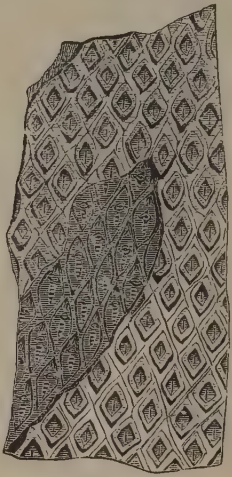

FIG. 494.

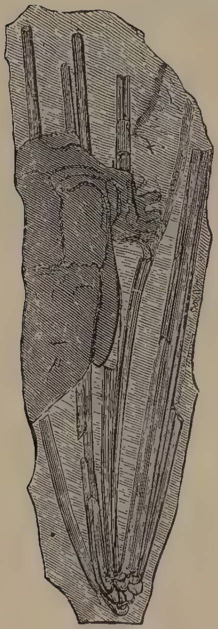

FIG. 498.

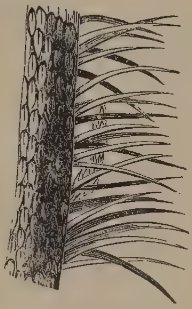

FIG. 496.

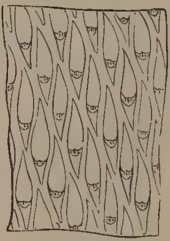

FIG. 495.

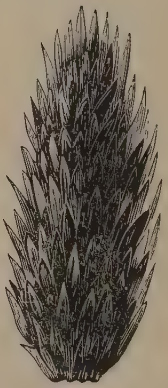

FIG. 499.

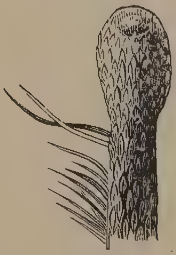

FIG. 497.

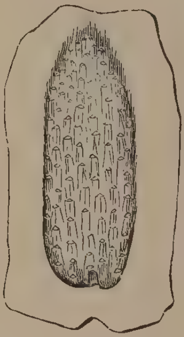

FIG. 500.

FIGS. 493-500.—LEPIDODENDRIDS: 493. Lepidodendron modulatum (after Lesquereux). 494. Lepidodendron diplotegioides (after Lesquereux). 495. Lepidodendron politum (after Lesquereux). 496. Lepidodendron corrugatum, branch and leaves (after Dawson). 497. Lepidodendron corrugatum, branch and fruit (after Dawson). 498. Lepidodendron rigens (after Lesquereux). 499. Lepidophloios Acadianus, fruit (after Dawson). 500. Lepidostrobus (after Lesquereux).

found in great abundance, and known under the name of *Lepidostrobus* (scale-cone), has shown that they bear in the axils of their scales *spores* like club-mosses, and not *seeds* like conifers. Also, like club-mosses, there are in some of these plants two kinds of spores*—microspores and macrospores. This would again ally them with conifers, for these organs may be said to represent the stamens and pistils of higher plants (Fig. 501). The external appearance and inflorescence, therefore, indicate that they are Lycopods, with very strong coniferous affinities.

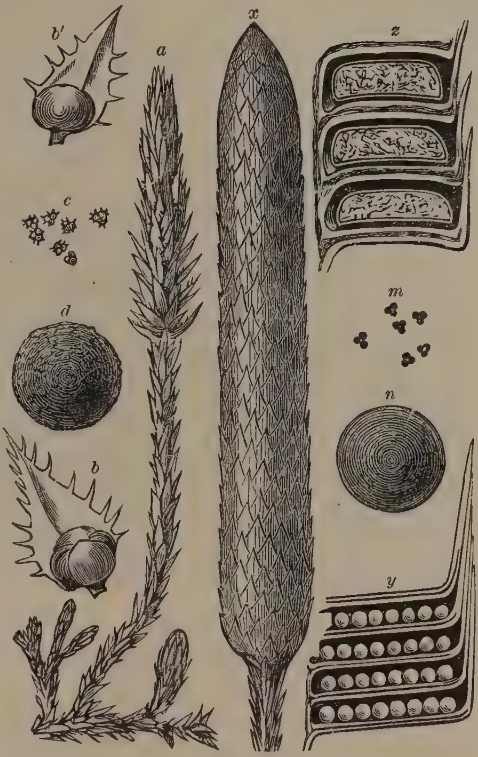

Fig. 501.—Lepidodendron compared with Club-Moss: *a*, club-moss; *b*, *b′*, scales enlarged; *b*, lower scales with macrospores; *b′*, upper scales with sporange containing microspores; *c*, microspores *d*, macrospores: *x*, lepidostrobus; *y* and *z*, the scales containing spores; *m*, microspores; *n*, macrospores (after Balfour).

This conclusion is entirely borne out by the *internal structure*. Fig. 502 represents an ideal cross and longitudinal section of the stem of a Lepidodendron. It is seen that the stem consists of a dense outer bark or rind, inclosing a great mass of loose cellular tissue or inner bark, through the center of which runs a comparatively small fibro-vascular cylinder, with very distinct pith. Bundles go from the cylinder outward to form the venation of the leaves. Now, the structure of a club-moss is almost the same, except that the fibro-vascular cylinder is solid, and there is, therefore, no *pith*. The presence in Lepidodendron of a distinct pith is an important char-

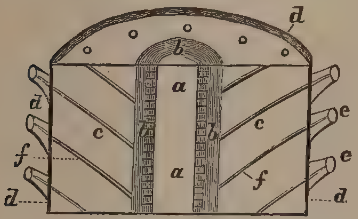

Fig. 502.—Ideal Section of a Lepidodendron: *a*, pith; *b*, vascular cylinder; *c*, inner bark; *d*, rind; *e*, bases of leaves; *f*, vascular threads going to the leaves.

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* Williamson, Nature, vol. viii, p. 498.

acter, placing it far above modern Lycopods, and allying it most decidedly with Exogens.

4. **Sigillarids.**—The typical genus of this family is *Sigillaria.* These plants are found, like Lepidodendrids, mostly as flattened masses, which are portions of trunks, but also as *roots* and *leaves.* The trunk-impressions are distinguished from those of Lepidodendrids by longitudinal ribbings or flutings, ornamented with seal-like impressions (*sigilla*, a seal), in vertical rows (Figs. 503–506). Little is known of their leaves, though they seem to have been similar to those of Lepidodendron (Fig. 507).

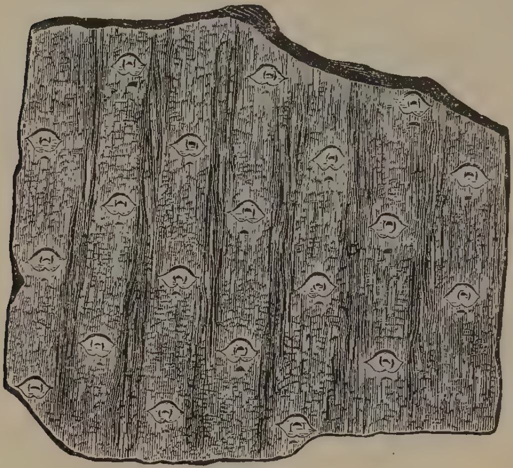

Fig. 503.

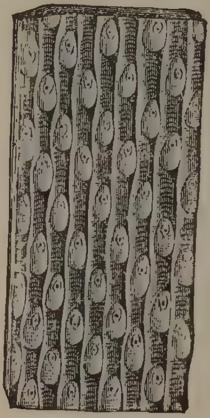

Fig. 504.

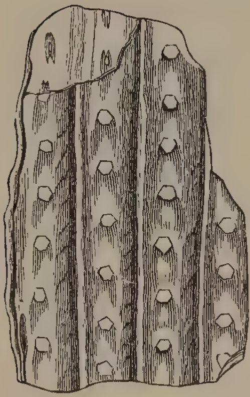

Fig. 505.

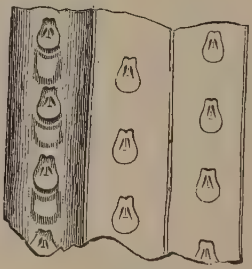

Fig. 506.

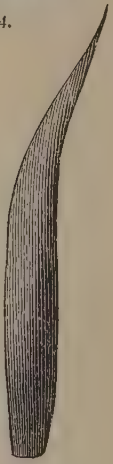

Fig. 507.

Figs. 503–507.—Sigillarids: 503. Sigillaria recticulata (after Lesquereux). 504 Sigillaria Græseri. 505. Sigillaria lævigata (European). 506. Sigillaria obovata (after Lesquereux). 507. Leaf of Sigillaria elegans (after Dawson).

The best general conception which we can form of the Sigillaria would represent it as a tall, gently-tapering trunk, longitudinally fluted like a Corinthian column, and ornamented with seal-like impressions in vertical ranks, representing the phyllotaxis; unbranched or else dividing only into a few large branches, clothed thickly with long, stiffish, tapering leaves. From the base of the trunk extended large, radiating roots, branching dichotomously and sparsely, with many long, thread-like rootlets penetrating the soil below. The stumps of Sigillaria and Lepidodendrons, with these large, horizontally-spreading roots and thread-like appendages, are very common in the under-clay, and were long supposed to be a peculiar plant, and called Stigmaria, on account of the round spots (*Stigma*) on their surface (Fig. 508). They are now known to belong to Sigillarids and Lepidodendrids, and are either roots or spreading rhizomes (underground branches).

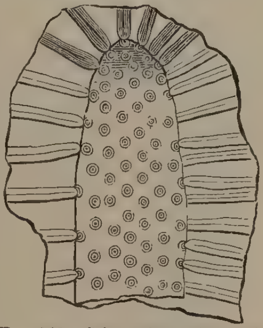

FIG. 508.—Stigmaria ficoides (after Lesquereux).

In the following figure (509), taken from Dawson, we have attempted to realize the general appearance of a Sigillaria. Their trunks were sometimes of prodigious length and diameter. They were probably the largest trees of the time. In a coal-seam in Dauphin County, Pennsylvania, flattened stems were found four feet and even five feet in width. Some of these were exposed for fifty feet, with but little apparent diminution. One was exposed sixty-five feet, and was estimated to have extended at least thirty feet more. Another was exposed seventy feet, and was estimated to have been eighty to one hundred feet when growing.*

The Sigillarids are regarded as closely allied to the Lepidodendrids. Indeed, the two families shade into each other in such wise that there are many genera the position of which, whether in the one family or in the other, is doubtful. The typical Sigillaria, however, differs in general port from the typical Lepidodendron, chiefly in possessing a more Palm-like, or Cycas-like, or Dracena-like stem. They are evidently, like the Lepidodendrids, closely allied to *Lycopods*, but their alliance with higher classes is even stronger than that of Lepidodendrids.

The internal structure of the stem entirely confirms this conclusion. A cross-section (Fig. 510) of a Sigillaria-stem shows a hard external rind, *d*, inclosing a great mass of loose, cellular tissue (inner bark), *c c*, through the center of which runs a comparatively small woody cylinder, *b b*, and in the center of this again a large pith, *a a*. From the woody cylinder go bundles of fibro-vascular tissue, *f f*, through the cellular tissue of the inner bark, to the leaves, *e e*. Thus far the description is like the Lepidodendron, except that the woody cylinder is larger and thicker; but closer examination shows, in addition, the woody cylinder divided into *woody wedges* by *medullary rays*, *g g*, in true exogenous style, though the concentric rings characteristic of Exogens are wanting. Still closer examination with the microscope shows, according to Dawson,* a *true gymnospermous tissue* (page 341, Figs. 392 to 394), both on cross and longitudinal section. This, however, is very doubtful. Now, there is no plant living which combines gymnospermous tissue with a general stem-structure at all similar to this, except *Cycads* (Cycas, Zamia, etc.). For the sake of comparison, we have given (Fig. 511) a cross-section of a Cycas; the letters represent the same as in the previous figure.

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* Taylor, Statistics of Coal, pp. 149, 150; Williamson, Nature, vol. viii, p. 447.

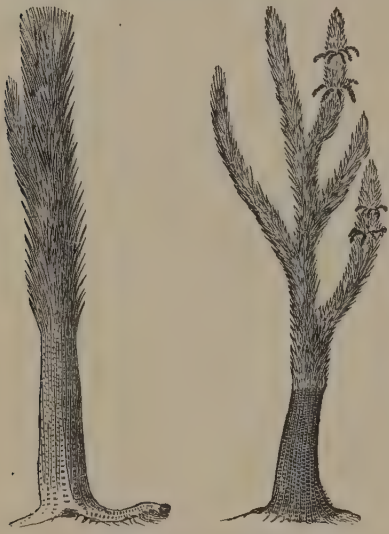

FIG. 509.—Restoration of Sigillaria, by Dawson.

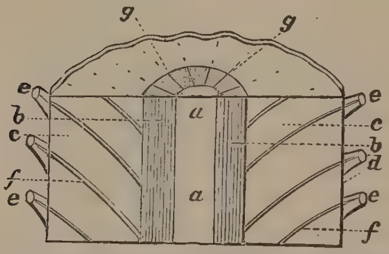

FIG. 510.—Ideal Section of a Sigillaria-Stem: *a*, pith; *b*, woody cylinder; *c*, inner bark; *d*, rind; *e*, bases of leaves; *f*, vascular thread running to the leaves; *g*, medullary rays.

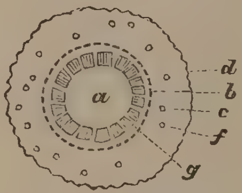

FIG. 511.—Cross-Section of Stem of Cycas.

Even leaving out the gymnospermous tissue as doubtful, there can be no reasonable doubt of the close alliance of the *Sigillarids* with the *Cycads*. But their close connection with Lepidodendrids shows an equally close, or closer, alliance with Lycopods. So thoroughly are they a connecting type that some paleontological botanists (Dawson) regard them as Cycads with strong Lycopod affinities, while most regard them as Lycopods with strong Cycad affinities. Recent investigations seem to substantiate the latter view; for, in connection with Sigillaria, inflorescence similar to that of Lepidodendrons, and containing spores, have been at last found.*

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* Acadian Geology, p. 530.

5. **Calamariæ.**—We include under this name, Calamites, Calamodendron Sphenophyllum, Annularia, etc. These are plants having long, slender, tapering, reed-like stems, jointed and hollow, or else with large pith. The exterior surface of the stem is finely striated, or fluted, but the striæ are not continuous nor marked with leaf-scars like the flutings of the Sigillaria, but are interrupted at the joints in the manner shown in Figs. 512 and 513. At the joints are attached in whorls the leaves, which are either scale-like, or strap-like, or thread-like. Sometimes at the joints of the main stem come out in whorls thread-like, jointed branches, bearing scale-like or thread-like leaves. At the lower end of the stem, the joints grow rapidly smaller and shorter, so that this end was conical. From these short, rapidly-tapering joints came out the *thread-like roots.* The stem was terminated above with a cone-like fruit (Fig. 517).

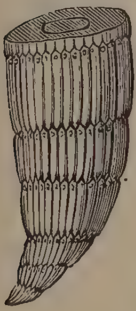
FIG. 512.

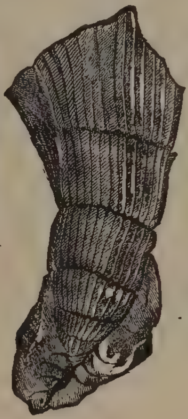
FIG. 513.

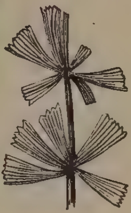
FIG. 514.

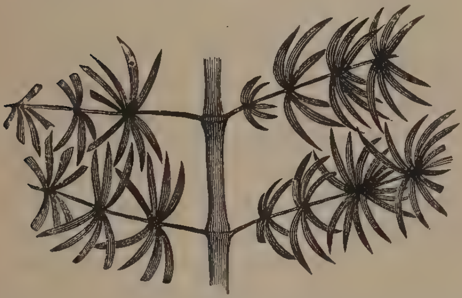
FIG. 515.

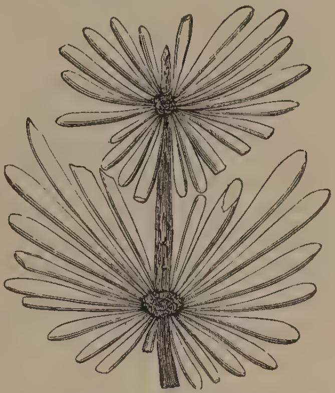
FIG. 516.

FIGS 512–516.—CALAMITES AND THEIR ALLIES: 512. Lower End of Stem of Calamites from Nova Scotia. 513. Lower End of Stem of Calamites cannæformis 514. Sphenophyllum erosum (after Dawson). 515. Asterophyllites foliosus, England (after Nicholson). 516. Annularia inflata (after Lesquereux).

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* Annales des Sciences Botaniques, vol. xix, p. 256, 1884.

What I have said thus far applies word for word to Equisetæ; but the Equisetæ of the present day are small, rush-like plants, never much thicker than the finger, and seldom more than three or four feet high, although in South America (Caracas) they grow thirty feet high, but are very slender; while Calamariæ were certainly two feet or more in diameter, and thirty feet high. Fig. 518 is an attempt to reconstruct the general appearance of a Calamite by Dawson.

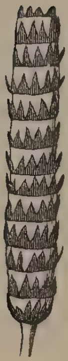
FIG. 517.—Fruit of Calamite (after Heer).

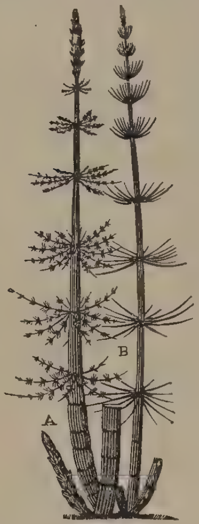

FIG. 518—Restoration of a Calamite (after Dawson).

The internal structure of Calamariæ still further removes them from Equisetæ; for they seem to have had (some of them, at least) a thick, woody cylinder of *exogenous structure*, i. e., growing by Cambrian layers. And if, as Williamson supposes,* many of the striated jointed stems called Calamites are only casts of the pith, the stems must have even been much larger than stated above.

Thus, as Lepidodendrids connected Lycopods with Conifers, and Sigillarids connected Lycopods with Cycads, so these connected Equisetæ with Conifers.

General Conclusion.—The conclusion which we draw from this examination of Coal plants is: 1. That they belong to the highest Cryptogams, viz., Vascular Cryptogams, and the lowest Phænogams, viz., Gymnosperms; 2. That they were intermediate between those now widely-separated classes, and connected them closely together. These facts are strictly in accordance with the law already announced (page 357), viz., that the earliest representatives of any class or order are not *typical* representatives of that class or order, but connecting or comprehensive types—that is, types which, along with their distinctive classic or ordinal characters, united others which connected them with other classes or orders. Thus the now widely-separated classes and orders of organisms, when traced backward, in time approach each other more and more, and probably unite in one common stem, although we are seldom able to find the point of actual union. Thus, in this case, the now widely-separated Cryptogams and Phænogams, when traced backward, approach until in the Coal they are nearly, if not completely, united. The organic kingdom may be compared to a tree whose trunk is probably to be found, if found at all, in the lowest strata; its main branches begin to separate in the Palæozoic, the secondary branches in the Mesozoic, and so the branching continues until the extreme ramification, but also the flower and fruit, are found in the fauna and flora of the present day. The duty of the evolutionist is to trace each bough to its fellow-bough, and each branch to its fellow-branch, and thus gradually to reconstruct this tree of life, and determine the *law* and the *cause* of its growth.

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* Nature, vol. viii, p. 447.

Theory of the Accumulation of Coal.

There is no question connected with the Carboniferous period concerning which there has been more discussion than the mode in which coal has been accumulated. There are some things, however, about which there is little difference of opinion. These we will state first, and thus narrow the field of discussion.

Presence of Water.—That coal has been accumulated in the presence of water, or at least of abundant moisture, is evident: *a.* From the *preservation* of the organic matter. By aërial decay vegetable matter is either entirely consumed, or else crumbles into dust. Only in the presence of water is it preserved and accumulated in larger quantities. *b.* The interstratified sand and clays and limestones have, of course, been deposited like all strata in water. *c.* The coal itself is not unfrequently distinctly and finely *stratified.* *d.* The plants found in connection with the coal-seams are mostly such as grow in moist ground.

Thus far, then, theorists agree, but from this point opinions diverge, and until recently have very widely diverged. Some have thought that coal has accumulated by the growth of plants "*in situ*," as in peat-bogs and peat-swamps of the present day. Others have supposed that it has accumulated by driftage of vegetable matter by rivers, like the rafts now found at the mouths of great rivers of the present day. According to the one view, a coal-seam is an ancient *peat-swamp;* according to the other, it is an immense *buried raft.* The one is called the "*Peat-bog theory*," the other, the *Estuary or raft theory.*

Recently, however, scientific opinions have converged toward a common belief. We will not, therefore, discuss these two rival theories, but simply bring out what is most certain in the present views on this subject:

1. *Coal has been accumulated by growth of vegetation in situ, as in peat-swamps of the present day.* This fact is now demonstrable. The reasons for believing it are the following: *a. The purity of coal.* The coals of the American coal-fields are, with few exceptions, absolutely pure, i. e., the amount of ash is not greater than would result from the ash of the plants of which it is composed. The same is true of coals of most extensive coal-fields everywhere. Now, it has already

been shown (p. 149) that in extensive peat-swamps, like the Great Dismal Swamp, absolutely pure vegetable accumulations unmixed with sediment occur; but in buried rafts or drifted vegetable matter of any kind there must be a large admixture of mud. *b. The preservation of the most complex and delicate parts of the plant in their natural relations to each other.* Large fronds are spread out and pressed as in a botanist's herbarium. Delicate leaves are preserved with all their finest venation perfectly visible. This is exactly what we would expect if they lay where they fell, but it is incompatible with driftage by rapid currents to long distances. *c. The position of these perfect specimens only on the upper part of the seam*, as would be the case with the *last* fallen leaves, instead of mixed throughout the seam, as would be the case with drifted matter. *d. The presence of stumps with their spreading roots penetrating the under-clay exactly as they grew.* This is not an occasional phenomenon, but is found in the under-clay of very many coal-seams. In South Wales there are 100 seams of coal, every one of which is underlaid by clay crowded with roots and sometimes with stumps. In Nova Scotia there are seventy-six seams, twenty of which have erect stumps standing in their original position with spreading roots still penetrating the under-clay. The other seams have each its under-clay filled with stigmaria-roots. Besides these seams there are many dark bands (dirt-beds) indicating old forest-grounds.

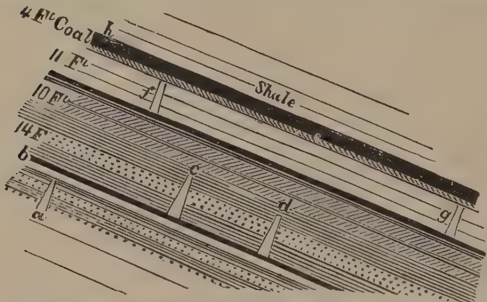

FIG. 519.—Erect Fossil Trees, Coal-Measures, Nova Scotia.

The following section (Fig. 519) shows some of these seams and dirt-beds or forest-grounds, with penetrating roots and erect trunks. Fig. 520 shows an area of about one quarter acre of surface of the under-clay of an English coal-seam in which there are seventy-three stumps *in situ*. This last evidence (*d*) is demonstrative. Beneath nearly every coal-seam there is a fossil soil—an ancient forest-ground.

Recapitulation.—We may sum up the evidence, and at the same time make it clearer, by describing a section of a peat-bog, and comparing with a coal-seam. In such a section we have always an under-clay, on which accumulated the moisture, and on which grew the original trees of the locality. This under-clay is often full of roots and stumps of the original growth. Above this is a fine, structureless, carbonaceous mass, corresponding to the coal-seam. On this are the last-fallen leaves, not yet disorganized, and the still-growing vegetation. Now, imagine this overwhelmed and buried by mud or sand, the whole subjected to powerful pressure, and a slow subsequent process of bituminization; and we have a complete reproduction of the phenomena of a coal-seam with its accompanying under-clay filled with roots, and its black shale filled with leaf and branch impressions.

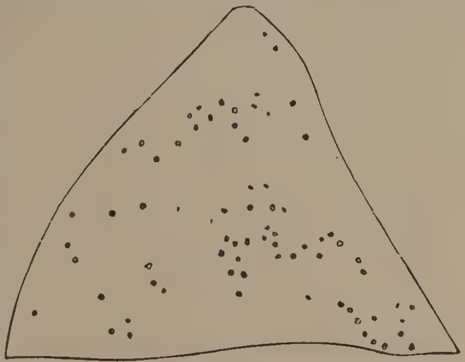
FIG. 520.—Ground-Plan of a Fossil Forest, Parkfield Colliery.

There are, however, many cases of coal-seams in which no evidences are found of forest ground. It seems probable, therefore, that coal was indeed accumulated *usually in situ* in extensive peat-swamps as already described; but that often in the center and lowest parts of these swamps there were shallow lagoons in which fine, partly decomposed material was accumulated by *gentle driftage;* and such drifted material formed often the finest and most structureless kinds of coal, like cannel and the like.*

2. *Coal has been accumulated at the mouths of rivers*, and therefore in localities subject to floods by the river and incursions by the sea. It is otherwise impossible to account for the clays and sands (often inclosing drift-timber), and limestones, interstratified with the coal. The phenomena of an *individual seam* prove the accumulation by growth *in situ;* the general phenomena of a *coal-basin*, with its succession of strata, prove that this took place at the mouths of rivers. Thus, the field of discussion is narrowed to very small limits.

We conclude, therefore, that coal has been accumulated in extensive peat-swamps at the mouths of great rivers, and therefore subject to occasional floodings by the river and inundations by the sea. That pure peat may accumulate under these circumstances, is sufficiently proved by the fact mentioned by Lyell, that over large tracts of ground in the river-swamp and delta of the Mississippi pure peat is now forming, in spite of the annual floods; the sediments being all stopped by the thick jungle-growth surrounding these spots, and deposited on the margins, while only pure water reaches the interior portions.†

But if coal has indeed been formed at the mouths of great rivers, we ought to find at least something analogous to a coal-field in sections of great river-deltas. And so, indeed, we do. We have seen (p. 143) that a great river-delta, like that of the Mississippi or the Ganges, consists of alternate layers of river-sediments (sands and clays) and marine sediments (limestones) with thin layers of peaty matter, and old forest-grounds with stumps and roots. It is, in other words, a coal-field, though an imperfect one, in the process of formation. It will be remembered, also, that we accounted for this alternation, not by oscillations, but by the operation of two opposing forces, one depressing (subsidence), the other up-building (river-deposit), with varying success. When the up-building by river-deposit prevailed, the area was reclaimed, and became covered with thick jungle vegetation; when the subsidence prevailed, it was again covered with water, and buried in river-sediments, etc. Now and then, when the subsidence was unusually great, the sea invaded the same area, and limestone was formed. It is substantially in this way that coal-fields were probably formed.

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* Grand Eury, Memoire sur la formation de la Houille.

† Lyell, Elements of Geology, p. 488.

Application of the Theory to the American Coal-Fields: *a.* **Appalachian Coal-Field.**—A glance at the map (p. 302) will show that, during Carboniferous times, there was high land to the north, east, and west of this field, and the black area, representing the Coal-measures, was then a trough, into which, therefore, drained rivers from every side except the south. This trough was sometimes a coal-swamp, sometimes a lake emptying southward, sometimes an arm of the sea connecting with the ocean southward. When it was a coal-marsh, a coal-seam was formed; when a lake, sands and clays were deposited by the rivers; when an arm of the sea, marine deposits—limestones—were formed.

This alternation of conditions we explain as follows: There were three forces at work on this area: 1. A general continental *upheaval*, affecting this along with all other parts of the continent; 2. An *up-building* by sedimentary deposit; 3. A *local subsidence.* The evidence of all these is complete. The continental upheaval, as we have already seen, was unceasing throughout the *previous* periods, and, as we shall see, continued throughout the subsequent periods. The up-building by sediments and the *pari passu* subsidence are as clearly marked as in deltas of the present day, by *shore-marks*, by *shallow-water* fossils, and especially by *forest-grounds* repeated through several thousand feet of vertical thickness. The existence of these three forces, therefore, is not a doubtful hypothesis. Now, the first two would tend to *reclaim*, the third to *submerge*, the area. When the reclaiming forces predominated, the area became swamp-land, and covered with coal vegetation, and the river-water, strained through the thick growth, slowly went southward by a kind of seepage. When the submerging forces predominated, the area became a lake, and sediments in great quantities were brought down by the rivers. It is possible, perhaps probable, that correlative with the more rapid local subsidence which formed the lake there was also a more rapid elevation of the high lands on all sides, producing more torrential river-currents and greater sedimentary deposits.

Now and then, at long intervals, the subsidence would bring the area below sea-level, and would thus form an interior sea, or mediterranean. During such times, limestones would be formed, and marine animals would be imbedded as fossils.

b. **Western Coal-Fields.**—The *Central* and *Western* coal-fields may be regarded as *one*, having been subsequently separated by denudation. This immensely extensive field *may* have been, like the Appalachian, a hollow surrounded on all sides by higher land. If so, the western land has since been submerged, and covered by more recent deposits. Or it may have been an extensive jungly flat, bordering a western sea, the many small rivers with inosculating deltas, flowing westward and seeping through the thick, marshy vegetation. There were here far less mechanical sediments, because less high land, and far more marine deposits, because there was a larger and opener sea; but, in other respects, the process may be regarded as similar.

Appalachian Revolution.—This state of oscillation and incertitude was cut short by the Appalachian revolution. At the end of the Coal period, the sediments which had been so long accumulating in the Appalachian region, until their aggregate thickness had now reached 40,000 feet, at last yielded to the horizontal pressure produced by interior contraction of the earth (p. 274), and were crumpled and mashed, and thickened up into the Appalachian chain. At the same time the Western coal-swamps were upheaved sufficiently to become permanent dry land. This revolution closed the Carboniferous age and the Palæozoic era.

Estimate of Time.

We have said (p. 287) that it is important that the mind become familiarized with the idea of the immense time necessary to explain geological phenomena. We therefore embrace this opportunity to make a rough estimate of the Coal period. The estimate may be made either by taking the whole amount of *coal* in a coal-field as the thing to be measured, and the *rate* at which vigorous vegetation now makes organic matter as the measuring-rod; or else by taking the whole *amount of sediments* in a coal-basin as the thing to be measured, and the *rate* of accumulation of sediments by large rivers as the measuring-rod. We will give both, though the latter is probably the more reliable:

1. **From Aggregate Amount of Coal.**—A vigorous vegetation—as, for example, an average field-crop or a thick forest—makes about 2,000 pounds of dried organic matter per annum per acre, or 200,000 pounds or 100 tons per century.* But 100 tons of vegetable matter pressed to the specific gravity of coal (1·4), and spread over an acre, would

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* Recent researches considerably increase these numbers. Nature, vol. xvi, p. 211, 1877.

make a layer less than two thirds of an inch in thickness. But, according to Bischof, vegetable matter in changing to coal loses, on an average, four fifths of its weight by the escape of CO_2, CH_4, and H_2O (p. 370), only one fifth remaining. Therefore, vigorous vegetation at present could make only about one eighth of an inch of coal, specific gravity 1·4, per century. To make a layer one foot thick would require nearly 10,000 years. But the aggregate thickness in some coal-basins is 100 feet, 150 feet, or even 250 feet (p. 363). This would require—the former near 1,000,000, the latter 2,400,000 years. It is probable, however, that coal vegetation was more vigorous than the present vegetation. Our measuring-rod may be too short; we will try the other method:

2. **From Amount of Sediment.**—We are indebted to Sir Charles Lyell for the following estimate of the time necessary to accumulate the Nova Scotia Coal-measures. This coal-field is selected because the evidences of river-sediments are very clear throughout. The area of this coal-basin is given on page 364 as 18,000 square miles; but the identity in character of portions now widely separated by seas—e. g., on Prince Edward's Island, Cape Breton, Magdalen Island, etc.—plainly shows that all these are parts of *one original field*, which could not have been less than 36,000 square miles. The thickness at South Joggins is 13,000 feet. At Pictou, 100 miles distant, it is nearly as great. We shall certainly not err on the side of excess, therefore, if we take the average thickness over the whole area as 7,500 feet. This would give the cubic contents of the original delta deposit as about 51,000 cubic miles. Now, the Mississippi River, according to Humphrey and Abbot, carries to its delta annually sediment enough to cover a square mile 268 feet deep, or nearly exactly *one twentieth of a cubic mile.* Therefore, to accumulate the mass of sediment mentioned above would take the Mississippi about 1,000,000 years.

It may be objected to this estimate that it is founded on a particular theory of the accumulation of the Coal-measures. The answer to this is plain. Any other mode would only extend the time, for this mode is more rapid than any other. Again, it may be objected that we have evidence of a very rapid accumulation in stumps and logs and erect trunks, either bituminized or petrified, and which, therefore, must have been completely buried before they could decay. The answer is, that these are only examples of *local* rapid deposit, and do not at all affect the general result. Precisely the same happens now in river-deltas. Again, it may be objected that the agencies of Nature were far more energetic then than now. This objection has already been answered on page 288.

We, therefore, return to our estimate with increased confidence that it is far within limits. But the Coal period, as already said (p.

360), is not more than one thirtieth of the *recorded* history of the earth; beyond which, again, lies the *infinite abyss of the unrecorded.*

Physical Geography and Climate of the Coal Period.

Physical Geography.—In the eastern part of the American Continent the area of land during this period is approximately shown in the map (p. 302). It included the Archæan, the Cambrian, the Silurian, and Devonian areas, during the whole age. In the sub-Carboniferous period the sub-Carboniferous and Carboniferous areas were covered by the sea, but in the Carboniferous period proper the sub-Carboniferous area was land, and the Carboniferous area, as already seen, was in an uncertain state, sometimes above and sometimes below the sea-level. It is probable, also, that the *Eastern border-land* extended then much beyond the line of the Tertiary deposits (see map, p. 302), and even beyond the present coast-line (see map, Fig. 269, p. 303), and was partly submerged in the elevation of the Appalachian chain, at the end of the Coal period.

In the Rocky Mountain region there were considerable bodies of land, mainly in the Basin region, but their limits are not accurately known.

Again, it is almost certain that all the lands were comparatively low. None of the great mountain-chains of the continent were yet formed. It is also probable that the same was true of the other continents. Nearly all the high mountain-chains are either more recent in their *origin*, or else in their principal *growth*. In general terms, then, the lands were smaller and lower, and the conditions more oceanic, than at present.

Climate.—The climate of the Coal period was undoubtedly characterized by greater *warmth*, *humidity*, *uniformity*, and a more highly *carbonated condition* of the atmosphere, than now obtain. Most of these characteristics, if not all, are indicated by the nature of the vegetation:

1. The *warmth* is shown by the existence of a tropical or ultra-tropical vegetation. Of the present flora of Great Britain about one thirty-fifth are Ferns, and none of these Tree-ferns. Of the Coal flora of Great Britain about *one half* were Ferns, and many of these Tree-ferns. At present in all Europe there are not more than sixty known species of Ferns: in European Coal-measures there are nearly 350* species, and these are certainly but a fraction of the actual number then existing. That this indicates a tropical climate is shown by the fact that out of 1,500 species of living Ferns known twenty years ago, 1,200, or four fifths, were tropical species. The number of known living Ferns is now about 3,000,† but the proportion of tropical species is

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* Lesquereux.

† Nature, August, 1876.

still probably the same. Even in the tropics, however, the proportion of Ferns is far less than in Great Britain during the Coal period. Again, Tree-ferns, arborescent Lycopods, Cycads, and Araucarian Conifers, are now wholly confined to tropical or sub-tropical regions. The prevalence of these tropical families and their immense size, compared with their congeners of the present day, would seem to indicate not only tropical but *ultra*-tropical conditions. And these conditions prevailed not only in the United States and Europe, but northward into polar regions; for *in Melville Island*, 75° *north latitude, Grinnell Land*, 81° 43′, *and Spitzbergen*, 77° 33′ *north latitude, have been found coal-strata containing Tree-ferns, gigantic Lycopods, Calamites*, etc.

2. The *humidity* is indicated by the fact that Tree-ferns and arborescent Lycopods are most abundant now on islands in the midst of the ocean; and further by the great extent of the Coal swamps, and perhaps also by the general *succulence* of, or the predominance of cellular tissue in, the plants of that period.

3. The *uniformity* is proved by the great resemblance and often identity of the species in the most widely-separated regions. According to Lesquereux, out of 434 American and 440 European species, 176 are common, and the remainder far less diverse in character than the species of the two floras at present. Again, in all latitudes, from the tropics to 75° north latitude, Coal species are extremely similar. Such uniformity of vegetation shows a remarkable uniformity of climate. From the earliest times until the present there has been probably a gradual evolution of continents—a gradual differentiation of land and water, a consequent differentiation of climates, and a corresponding differentiation of faunas and floras.

4. The *carbonated condition* of the atmosphere is proved by the large quantity of carbon laid up in the form of coal, the whole of which was withdrawn from the atmosphere in the form of *carbonic acid*. It is also indicated by the nature and the luxuriance of the vegetation. The proportion of carbonic acid in the atmosphere is now about $\frac{1}{20}$ per cent ($\frac{1}{2000}$). Now, since carbonic acid is the necessary food of plants, it is natural to expect that up to a certain limit the increase of atmospheric carbonic acid would increase the luxuriance of vegetation. Experiments by Daubeny* prove that this is *true especially for vascular Cryptogams.*

We may therefore picture to ourselves the climate of this period as *warm, moist, uniform, stagnant* (for currents of air are determined by *difference* of temperature), and *stifling*, from the abundance of carbonic acid. Such physical conditions are extremely favorable to vegetation, but unfavorable to the higher forms of animal life.

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* Report of British Association for 1849, p. 62, and 1850, p. 159.

Cause of this Climate.—The *moisture* and *uniformity* were the necessary result of the physical geography already given. They were due to the wide extent of ocean and the absence of large continents and high mountains. High mountains are the precipitating points for the atmosphere—points through which it discharges its superabundant moisture. As these did not exist, the atmosphere was always highly charged. The prevalence of the ocean also, as is well known, produces uniformity.

The greater *warmth* of *high latitudes* is partly explained by the *uniformity*. But there is good reason to believe that there was then a higher *mean temperature* than now exists. This was probably due not to the greater interior temperature of the earth, as usually supposed, but to the *constitution of the atmosphere*. This may be shown as follows:

The surface-temperature of the earth is now almost wholly due to *external*, not to internal causes. It has been calculated that only one twentieth of a degree Fahr. is now due to the latter cause. In going downward the heat increases about 1° Fahr. for every 50 to 60 feet, i. e., the *internal* heat for every 50 feet of depth increases twenty times the surface-temperature, so far as this is due to *internal* causes. Now, it has been shown by Fourier and Hopkins that the same would be true whatever be the surface-temperature from internal causes. For example, if the surface-temperature from internal causes be 1°, then for every 50 feet of depth the interior heat would increase 20°. If the surface-temperature from internal causes be 10°, then for every 50 feet of depth the interior heat would increase 200°—a condition of things entirely inconsistent with the growth of plants, since all the springs would be boiling. We can not, therefore, attribute, as many have done, even a few degrees' increase of mean temperature to causes interior to the earth. In fact, it seems almost certain that during the whole recorded history of the earth, i. e., during the time it has been inhabited by organisms, the surface-temperature of the earth has been almost wholly due to external causes. Now, the composition of the atmosphere is an external cause, which greatly affects the surface-temperature, but which has hitherto been almost wholly neglected. The thorough explanation of this point will require some discussion of the properties of transparent media in relation to light and heat.

Many bodies which are transparent to light are opaque to heat. Such bodies, however, will freely transmit heat, if the heat be accompanied with intense light. It is as if the light carried the heat through with it. Heat thus associated with light is sometimes called *light-heat*, while that which is not thus associated is called *dark heat*. Now, the bodies spoken of are *transparent* to light-heat, but *opaque* to dark heat.

Glass is such a body. If a pane of glass be held between the face and the *sun*, the heat passes freely and burns the face, but the same pane would act as a *partial* screen before a *fire*, and as a *perfect* screen before a hot, but not incandescent, *cannon-ball*.

It is in this way we explain the fact that a glass greenhouse, even in the coldest sunshiny winter's day, becomes insupportably warm if shut up. The sun-light and heat pass freely through the glass, and heat the ground, the benches, the flower-pots; but the light-heat thereby becomes converted into dark heat, and thus is *imprisoned* within.* Now, the *earth and its atmosphere are such a greenhouse.* The light-heat passes readily through, warms the ground, changes into dark heat, and is in a measure imprisoned by the partial opacity of the atmosphere to this kind of heat. The atmosphere is a kind of blanket put about the earth to keep it warm. So much has long been recognized. But Tyndall has shown † that the property of opacity to dark heat in the case of the atmosphere is due wholly to the small quantity of carbonic acid and aqueous vapor present; that oxygen and nitrogen are transparent to dark heat, and, therefore, if the atmosphere consisted only of these two gases, it would not be heated by radiation from the earth, and the ground would lose all its heat by radiation during the night, and become intensely cold like space. In other words, the blanket put about the earth to keep it warm is woven of carbonic acid and aqueous vapor.

Now, we have seen that during the Coal period *the quantity of carbonic acid and aqueous vapor* ‡ in the air *was far greater* than now. The atmosphere was then a *double blanket*, and therefore kept the young earth much warmer. We believe that Prof. T. S. Hunt # was the first to apply this discovery of Tyndall to the explanation of the climate of the Coal period. E. B. Hunt had previously attributed it to greater density of the air; but this is a wholly different principle.‖

Thus the physical geography explains the humidity and uniformity, and the greater humidity and the carbonic acid explain the greater mean temperature. But there is still the carbonic acid to be accounted for.

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* On Mount Whitney, in the sunshine, Langley got, in a box covered with glass, a temperature of 236° Fahr. or 113·3° C., while in the shade of the open air the temperature was only 58·6° F. or 14·8° C.

† Proceedings of the Royal Society, vol. xi, p. 100; American Journal, second series, vol xxxvi, p. 99.

‡ This does not mean clouds or fogs, but transparent invisible vapors.

Chemical and Geological Essays, p. 42.

‖ According to Buff, Archives des Sciences, vol. lvii, p. 293, the opacity to dark heat of carbonic acid and aqueous vapor has been exaggerated by Tyndall.

The more *highly-carbonated condition* of the atmosphere must be attributed to the original constitution of the air. All carbonic-acid-producing causes, such as animal respiration, combustion, general decay of organic matter, volcanoes, carbonated springs, etc., only *return* to the air what has been previously taken from it. There can be no doubt that all the carbon in the world, whether in the form of organic matter, or of coal, or of bitumen, or of carbonates, existed once as carbonic acid in the air, and has been progressively withdrawn. First immense quantities were withdrawn and fixed as carbonates, especially as carbonate of lime (limestone), and the air correspondingly purified. Again, immense quantities were withdrawn by the luxuriant vegetation of the Coal period, and fixed as *coal*. In this latter method of withdrawal the oxygen of the carbonic acid is returned, and the oxygenation of the air is increased. We shall see hereafter that the process of purification did not cease with the Coal period; for large quantities were again withdrawn and laid down as coal and lignite in the Jurassic, the Cretaceous, and Tertiary periods. There can be no doubt that this progressive purification of the air, by the withdrawal of superabundant carbonic acid and returning the pure oxygen, fitted it for the purposes of higher and higher animals.

Iron-Ore of the Coal-Measures.

We have already stated that the Coal-measures consist of alternating layers of sandstones, shales, and limestones, containing seams of *coal* and bands of *iron-ore*. We have already discussed the mode of *occurrence*, the *varieties*, and the *theory* of accumulation of the *coal*. We come now to discuss the same points in regard to the *iron-ore*.

Mode of Occurrence.—The mode of occurrence of iron-ore is, in many respects, like that of coal. Like coal, it is found in seams, which vary in thickness from a fraction of an inch to forty or fifty feet. Like coal, these very thick seams are apt to be impure, being largely mixed with clay. Seams pure enough to work profitably are seldom more than three or four feet thick. Like coal, the seams are repeated many times in the same section (Fig. 454, p. 361), but without any discoverable order of succession. Like coal, the seam is usually *underlaid by clay*.

Kinds of Ore.—The form of iron-ore found in all strata, except those containing coal, is usually *ferric oxide*, either hydrated (brown hematite—limonite), or anhydrous (red hematite), or else magnetic oxide; but in the Coal-measures of this period, and in the Coal-measures of every *other period*—i. e., in *all strata containing coal*—the iron is in the form of *ferrous carbonate*. This is usually mixed with clay, and therefore called *clay iron-stone*. It is often nodular and mammillated, and called *kidney iron-ore*. Sometimes it is mixed intimately with carbonaceous matter, and is called *black-band ore.* This last very valuable ore is found in Pennsylvania, Ohio, and in Scotland.

The importance of the association of coal and iron in the same strata can not be overestimated. For this reason, the raising of coal and the manufacture of iron are conducted in connection with each other, and the smelting furnaces are often situated at the mouths of the coal-mines. It is easy to understand, therefore, why Great Britain, the greatest coal-producing country in the world, should be also the greatest iron-producing country. Most of the iron-ore worked in Great Britain is taken from her coal-measures. In this country, much iron is made from the iron carbonates of the coal-measures, but much also from the peroxide and magnetic ores found elsewhere, especially in Archæan (p. 298).

The following table gives a comparative view of the annual iron-production, in tons, of the principal iron-producing countries of the world. It will be seen that Great Britain makes more than a third of the iron of the world. The rapid increase in the production of this great agent of civilization is also seen. In 1888 the iron and steel production of the United States reached the enormous amount of 12,000,000 tons:

IRON AND STEEL.	1845.	1856.	1864.	1871.	1873.	1884.
Great Britain....	2,200,000	3,500,000	5,000,000	5,667,000	6,566,000	10,600,000
United States....	502,000	1,000,000	1,200,000	....	2,560,000	6,200,000
France	450,000	....	1,217,000	....	1,381,000	2,600,000
Germany........	....	....	....	1,664,000	....	4,500,000
World..........	....	7,000,000	....	....	14,485,000	27,300,000

Theory of the Accumulation of the Iron-Ore of the Coal-Measures.— We have already explained (p. 150) how iron-ore is *now* accumulated by the agency of decaying organic matter. We have also shown that if the organic matter is consumed in doing the work of accumulation, the iron-ore is left in the form of iron peroxide; but if it is accumulated in the presence of excess of organic matter, it retains the form of ferrous carbonate. We will now give additional evidence, taken from the occurrence of iron-ore in the strata of the earth, that the same agency has accomplished the same results in all geological times:

1. Immense beds of iron-ore are found in the strata of all geological ages; but, wherever we find them, we find also associated a corresponding amount of strata, decolorized or leached of their iron coloring-matter. Contrarily, wherever we find the rocks extensively *red*, we usually find also an absence of valuable beds of iron-ore. We are thus led to conclude that the *iron-ore* of iron-beds *has been washed out of the strata*, which are thereby left in a decolorized condition.

2. That this has been done by the agency of organic matter is shown by the fact that, wherever we find evidences of organic matter, whether in the form of *fossils* or of *coal*, we find the sandstones and shales are white or gray—i. e., leached of coloring-matter. Conversely, red rocks are usually *barren* of *fossils* or of *coal*. For example, all the sandstones of the coal-measures, or of all other strata containing coal, are *gray*, while the Old Red sandstone below the coal, and the New Red sandstone above the coal, and, in fact, all red sandstones, are very poor in fossils or evidences of organic matter of any kind. Thus, evidences of organic matter, and the decoloring of the strata, and the accumulation of iron-ore, are closely associated as cause and effect.

3. In all the strata, whether older or newer, in which there is no coal, i. e., in which there is no excess of organic matter in a state of change, the iron-ore is peroxide (*ferric* and magnetic oxide); while in coal-measures of all periods, whether Carboniferous, or Jurassic, or Cretaceous, or Tertiary, or in all cases where there is organic matter in excess in a state of change (not graphite), the iron-ore is in the form of carbonate protoxide, or *ferrous* carbonate ($FeCO_3$).

Therefore, we conclude that both *now* and *always* iron-ore is, and has been, accumulated by organic agency;* again, that both now and always there are, and have been, three conditions of iron-ore, each associated with the absence or presence in smaller or larger quantities of changing organic matter: 1. It may be universally diffused as a coloring-matter of rocks and soils, and unavailable for industries; in this case there has been no organic matter to leach it out and accumulate it. 2. It may be accumulated as ferric oxide; in this case there has been organic matter only sufficient to do the work of accumulation, and was all consumed in doing that work. 3. It may be accumulated as ferrous carbonate; in this case there is excess of organic matter, usually in the form of *coal*.

This much is certain; but, as to the exact mode and time of the leaching and accumulation, there is some difference of opinion. There are two ways in which the accumulation may have occurred: It may have accumulated *in the coal-marshes during the Coal period*, being at that time leached out of the surrounding soils, which were therefore left in a decolorized condition, and in this condition subsequently washed down as sediments into the coal-marshes. Or, it may have been brought down as the coloring-matter of red sands and clays; and *afterward*, perhaps after the Coal period, leached out by percolating waters containing organic matter from the coal-beds, carried downward until stopped by an impervious clay-stratum, and accumulated there. The former mode is the more probable.*

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* Some writers have contested this statement. See Winchell, Minnesota Geological Survey, Bulletin VI, pp. 246–248, 1891.

The above view is true as a *general* statement, but the accumulation is not always direct. On the contrary, it may be (*a*) by replacement of limestone by ferrous carbonate which becomes oxidized into ferric oxide; or (*b*) ferrous sulphate may react with lime carbonate and form lime sulphate and ferrous carbonate ($FeSO_4 + CaCO_3 = CaSO_4 + Fe CO_3$), the latter becoming by oxidation ferric oxide; or, finally (*c*), ferriferous limestone may be leached of its lime and the residual iron accumulated.

But, in any case, organic matter has been the agent in some stage of the change; and, therefore, in this case, as in all other cases, iron-ore is the *sign* of organic matter, and the *measure* of the amount of organic matter consumed in its accumulation. There are, therefore, three signs of the previous existence of organisms used by geologists; they are *coal*, *iron-ore*, and *fossils*.

We can not dismiss this subject without making one passing reflection suggested by the mention of these three signs of life:

The organic kingdom is so much matter taken from the atmosphere, embodied for a brief space in individual living forms, to be again dissolved by death, and returned to the atmosphere whence it came. The same material is again taken by the next generation, embodied and again returned at its death. The same small quantity of matter in the atmosphere is embodied and disembodied, again embodied and disembodied, and thus worked over and over again by constant circulation thousands, yea, millions of times, in the history of the earth. Now, in this constant circulation of the elements of organic matter, besides the work done in the fact of circulation itself, viz., the wonderful but fleeting phenomena of vegetable, animal, yea, of human life, there was another work, the results of which accumulated from age to age—a work, too, of the greatest importance to the well-being of the human race. *A portion* of this circulating matter, in its course downward from the organic to the mineral kingdom, *stopped half-way*, and was accumulated as great beds of *coal*—reservoirs of stored force. As circulating water descending seaward is stopped and stored in reservoirs to complete its descent under the control of man, and do his work; so circulating organic matter descending is stopped and stored, and is now completing its descent under the control of man, and doing his work, and thus becomes the great agent of modern civilization.

A second portion of circulating organic elements *completes* its descent, but in doing so accumulates iron-ore, the second great civilizer of the human race.

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* Bischoff, Chemical Geology, vol. i, p. 315.

A third portion also completes its descent, but accumulates neither coal nor iron-ore; but it accomplishes a work far more subtile and beautiful than either of the others. As each particle of organic matter returns to the atmosphere, it compels a particle of mineral matter to take its place, thus completely reproducing its form and structure. Thus fossils are formed, and thus is the history of the organic kingdom self-recorded. Thus, while the other two portions have subserved the material wants of man, this portion has subserved his higher intellectual wants.

Bitumen, Petroleum, and Natural Gas.

The origin of bitumen and petroleum is so similar to that of coal, that although not confined to, nor even found principally in, the Coal-measures, the subject is best taken up in this connection.

It is well known that coal or any organic matter, by suitable distillation, may be broken up into a great variety of products: some solid, as *coal-pitch;* some tarry, as *coal-tar;* some liquid, as *coal-oil;* some volatile, as *coal-naphtha;* and some gaseous, as *coal-gas.* Now, we find collected, in fissures beneath the earth, or issuing from its surface, a very similar series of products: some solid, as *asphalt;* some tarry, as *bitumen;* some liquid, as *petroleum;* some volatile, as *rock-naphtha;* and some gaseous, as *marsh-gas* of burning springs. There can be little doubt that these also *are of organic origin.* The utilization of all these products, especially petroleum and gas, have now become a great industry.

Geological Relations.—Bitumen and petroleum are found in all fossiliferous rocks, from the lowest Silurian to the uppermost Tertiary, under certain conditions, among which are the local abundance of organisms from which these substances are formed, and the absence of great metamorphism. The *signs* of their presence in any locality are iridescent scums on the water of springs (oil-show), and the issuing of combustible gases (burning springs). In regard to the first sign, it must be remembered that iridescent scums are produced by many other substances besides petroleum. The second sign is considered the best, although combustible gases may issue from decomposing organic matter of any kind, or from coal. Some of the burning springs in the oil-region of Kentucky are said to produce a flame twenty to thirty feet long. It is a significant fact that petroleum is often *associated with salt.* It is so in Pennsylvania, in Virginia, and in many other localities.

Oil-Formations.—I have said that petroleum and bitumen are found in all fossiliferous formations, but in each country there are certain formations where it especially abounds: in Europe it is found principally in the Tertiary; in Eastern United States it is found almost wholly in the Palæozoic, below the Coal-measures; in California it is found in the Tertiary.

Principal Oil-Horizons of the United States.—In Pennsylvania and Kentucky oil is found in the Upper Devonian; in Canada, in the Lower Devonian; in West Virginia, in the sub-Carboniferous; in Ohio, in the Coal-measures, Upper Devonian (Huron shales), and especially in the Lower Silurian (Trenton limestone); in Colorado it is found in the Cretaceous: in California, in the Miocene Tertiary of the Coast Range, all the way from Los Angeles to Cape Mendocino. These have been called oil-horizons.

Laws of Interior Distribution.—The mode of interior distribution of petroleum is similar to, yet different from, that of water. Like water, it collects in porous strata, especially if these are covered with impervious strata, and in fissures and cavities of all kinds; like water and with water, it collects in ordinary wells, or sometimes spouts in immense quantities from artesian wells. Some of the great spouting-wells in Pennsylvania, when first opened, yielded 3,000 barrels per day, some in Ohio 5,000 barrels, or even more, and some of the great wells of Baku, on the Caspian Sea, even 1,000,000 gallons, or 25,000 barrels per day. But, unlike water, *there is no perennial large supply;* the accumulations of ages being exhausted sometimes in a few years. Unlike water, the force of ejection is not hydrostatic pressure *directly*, but hydrostatic pressure transmitted through elastic compression of the gases generated from the petroleum itself. The great spouting-wells, therefore, being the fortunate tappings of the accumulations of ages, in fissures and cavities, are enormously productive when first opened, but are also in the same proportion rapidly exhausted. It is evident that the same is much more true of gas-wells: they must be still more short-lived. In cases where the accumulation occurs in pores and numerous small fissures, the supply is less abundant but more permanent; although some very productive wells have been opened in porous sandstones of Pennsylvania and the limestones of Ohio where no decided cavities have been demonstrated. Where oil is associated with water and gas, especially in cavities, the three materials arrange themselves in the order of their specific gravities. It follows, therefore, that gas and oil usually come up first, and water only after these are exhausted.

Kinds of Rocks which bear Petroleum.—As already stated, petroleum, like water, is found principally in pores, fissures, and cavities of all kinds. The same kinds of rocks, therefore, which are water-bearing are also oil-bearing—viz., *sandstones and limestones*, especially if these have an impervious shale cover. In Canada and Ohio it is found in limestone, and the peculiar porous character of the Trenton limestone of Ohio which makes it oil-bearing is shown in Figs. 521 and 522. In

Pennsylvania it is found in sandstone with intervening barren shales. In Pennsylvania there are three oil-bearing sandstones separated by about 200 feet of intervening shales. If a well reaches the first sandstone without finding oil, the boring is continued to the second, or even to the third. Fig. 523 (taken from Lesley) represents a section through the Pennsylvania oil-regions, showing the three principal oil-horizons of the Eastern United States recognized at that time, viz., the Venango County (Pennsylvania) horizon with its three sandstones; the Virginia sub-Carboniferous horizon above; and the Canada horizon below. To these must now be added the Trenton limestone horizon of Ohio, still lower. It is probable that the oil-generating stratum is usually a shale. Above this is the oil-reservoir stratum of sandstone or limestone. Above this again is the impervious shale-cover.

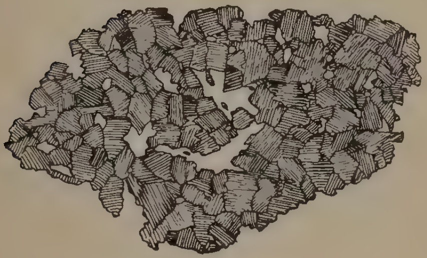

Fig. 521.

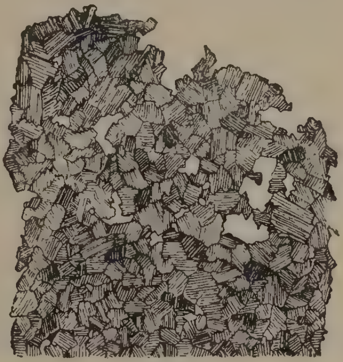

Fig. 522.

Figs. 521 and 522.—Sections of Trenton limestones of Ohio, magnified (from Orton).

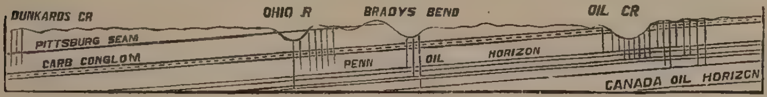

Fig. 523.

Petroleum (especially the lighter oils) is usually found only in horizontal or gently-folded strata, because strongly-folded and crumpled strata are always metamorphic, and the heat which produced metamorphism has also concreted the oil into bitumen or asphalt. Also the outcropping of the edges of highly-inclined strata favors the escape of gas and the concretion of the oil. It is hardly probable, therefore, that a light oil will ever be found in the California oil-region.*

In gently-folded strata the most productive portions seem to be along a line of anticline; because there we may expect large fissures, and also, perhaps, because the oil working up on the surface of water, is apt to accumulate under the saddles of the strata.

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* Some tolerably good oil has been found in California in metamorphic strata.

In California asphalt in very pure condition occurs in the form of *dikes*, filling great fissures in Miocene sandstone of the Coast Range. It is probable that its source is a bituminous or petroliferous underlying shale. Crust movements produced fissures, and pressure squeezed the liquid matter in a pure form into the open fissures, where it concreted as asphalt. The same phenomenon is observed in West Virginia and in Bulgaria.

Origin of Petroleum and Bitumen.

We have seen that the whole petroleum and bitumen series may be made artificially by destructive distillation of coal. There seems also to be little doubt that certain organic matters at *ordinary* temperature, in presence of abundant moisture, and out of contact of air, will undergo a species of decomposition or fermentation by which an oily or tarry substance, similar to bitumen, is formed. In the interior of heaps of vegetable substance such bituminous matter is often found.

There are therefore two general theories of the origin of petroleum: one, that it is produced by the distillation at high temperature of bituminous coal by volcanic heat, the coal being left as anthracite; the other, that it is formed at ordinary temperature by a peculiar decomposition of certain organic matters. The evidence in favor of the first view is the similarity between the artificial and the natural series; the objection to it is that the occurrence of petroleum seems to have no necessary connection with the occurrence below of coal-seams, and also that petroleum is found mostly in strata which have not been subjected to any considerable heat.

The argument for the other view is the fact that we actually find fossil cavities in solid limestone containing bitumen, evidently formed by decomposition of the animal matter. So, also, shales have been found in Scotland filled with fishes, which have changed into bitumen.

The most probable view seems to be that both coal and petroleum are formed from organic matter, but of different kinds and under slightly different conditions—that coal is formed from *terrestrial* vascular plants, in the presence of *fresh water*, while bitumen and petroleum are formed from more *perishable cellular* plants and microscopic animals, in the presence of *salt-water*. We have already noticed the frequent association of petroleum and salt. It is not improbable that ooze highly charged with organic matter, especially foraminifers and diatoms, under favorable conditions will form a bituminous shale such as seems to be the usual source of all these products.*

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* The chemist Mendeljeff has revived the theory of the mineral origin of petroleum. According to him, it is probably made by reaction at high temperatures of vapor of water

According to this view, taking the composition of petroleum as C_nH_{2n+2}, the reaction by which it is formed from vegetable matter is expressed in the following:

$$\begin{array}{ll} \text{Cellulose}\dots\dots\dots\dots & C_{36}H_{60}O_{30} \\ \text{Subtract}\left\{\begin{array}{c} 15CO_2 \\ 8CH_4 \end{array}\right\}\dots\dots\dots\dots & C_{23}H_{32}O_{30} \\ \cline{2-2} \text{And there remains}\dots\dots\dots\dots & C_{13}H_{28} = \text{petroleum.} \end{array}$$

Origin of Varieties.—However formed, there can be no doubt that the different varieties of this series are formed from one another by a subsequent process. It is certain that from all varieties CH_4 is constantly passing off, and that the result of this, together with oxidation, is a slow consolidation. By this process light oil is changed into heavy oil, heavy oil into bitumen, and bitumen into asphalt. Some of the grandest fissure-reservoirs of oil have thus been changed into solid asphalt. In the upper barren Coal-measures of West Virginia there is a vein of asphalt (Grahamite) four feet thick, over 3,000 feet long, and of unknown depth. It fills a great fissure which breaks through the rocks nearly perpendicularly, and outcrops on the surface.

There are, therefore, two series of substances formed from organic matter, viz., the coal series and the oil series. In each series the proportion of carbon increases by subsequent change until, perhaps, pure carbon may be reached. In the coal series we have fat coal, bituminous coal, semi-anthracite, anthracite, and, finally, graphite. In the oil series we have light oil, heavy oil, bitumen, asphalt, probably jet, and possibly, finally, *diamond:* for Liebig has suggested that diamond is most probably formed by crystallization of carbon from a liquid hydrocarbon, in which the proportion of carbon is constantly increasing by loss of CH_4.*

Future of this Industry.—The oil in the United States is practically inexhaustible. The finding of great reservoirs, producing spouting-wells, has always been, and always will be, very uncertain, and the duration of their productiveness limited; but a moderate return for industry and capital is certain for an almost unlimited time. A large portion of the Palæozoic basin, including an area of about 200,000 square miles, is underlaid by rocks which are more or less oil-bearing. The eastern portion of the United States (unless we except the borders of the Caspian Sea about Baku) is the great oil-bearing, as it is the great coal-bearing, country of the world. The gas supply will probably be much more quickly exhausted.

(H_2O) on carbide of iron (F_2C). It is hardly probable that geologists will accept this view. Other forms of the chemical theory have been more recently advanced.

* This view seems to be confirmed by recent observations in South Africa and South America. (Lewis, Science, vol. viii, p. 345; Derby, Science, vol. ix, p. 57).

Fauna of the Carboniferous Age.

As heretofore, we will disregard the subdivisions, and treat of the fauna of the whole age, or at least the two periods sub-Carboniferous and Carboniferous, together. It must be borne in mind, however, that most of the lower marine animals mentioned are from the sub-Carboniferous, while most of the fresh-water and land animals are from the Coal-measures. We can notice only what important families are going out, what important families are coming in, and a few which are very characteristic. We shall dwell only on what bears on the progress of life.

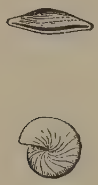


Fig. 524.—Fusulina cylindrica, magnified.

Among *rhizopods Fusulina* (Fig. 524) is very abundant and characteristic of certain limestones and shales of this age in the Mississippi Valley and westward to the Pacific coast.

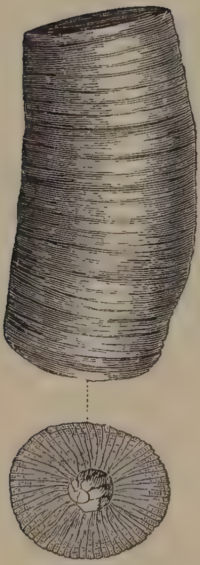


Fig. 525.

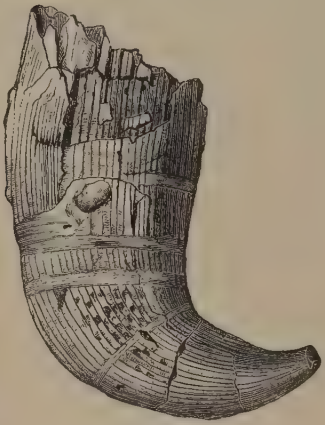
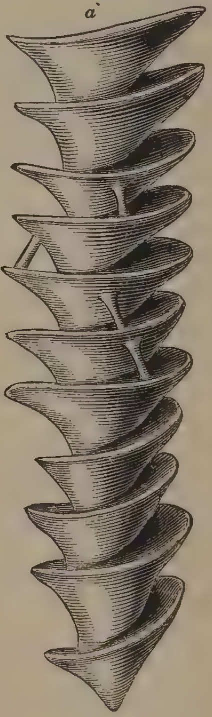


Fig. 526.



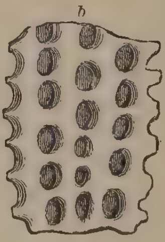


Fig. 527.

Figs. 525–527.—Carboniferous Rhizopods, Bryozoa, and Corals: 525. Lithostrotion Californiense (after Meek). 526. Clisiophyllum Gabbi (after Meek). 527. *a*, Archimedes Wortheni (after Hall); *b*, portion of frond, enlarged to show structure.

Among *corals* the same general characteristic Palæozoic type

(Quadripartita) continues to prevail, though in greatly-diminished variety of families; for the Favositidæ and Halysitidæ have passed away, and only the Cyathophylloids, or cup-corals, remain. The most beautiful and characteristic are the Columnar Lithostrotion (Fig. 525), a polyp-coral, and the curious corkscrew-like Archimedes (Fig. 527), a Bryozoan.

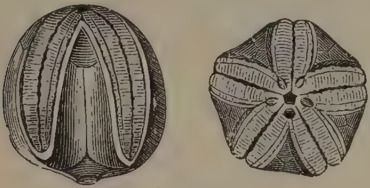


Fig. 528.

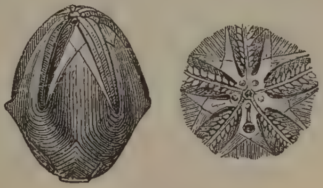


Fig. 529.

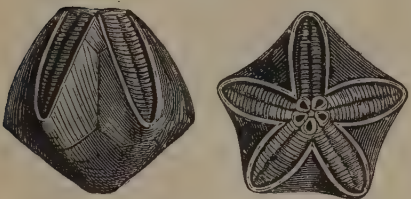


Fig. 530.

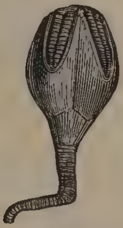


Fig. 531.

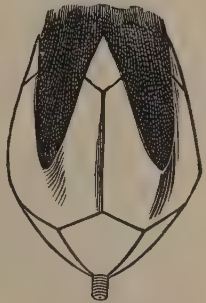


Fig. 531a.

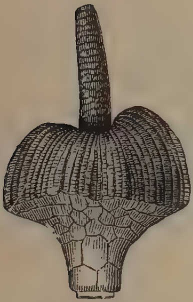


Fig. 532.

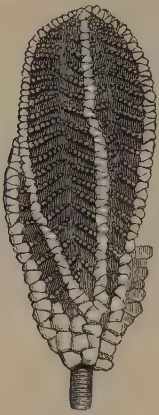


Fig. 533.

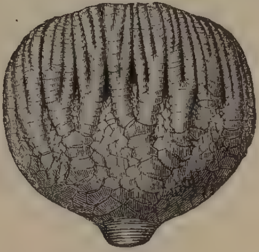


Fig. 534.

Figs. 528–534.—Echinoderms of the Carboniferous Age—*Blastoids:* 528. Pentremites Burlingtoniensis (after Meek). 529. Pentremites gracilis (after Meek). 530. Pentremites cervinus (after Hall). 531. Pentremites pyriformis (after Hall). 531a. Pentremite restored (after Lütken). *Crinids:* 532. Batocrinus Chrystii (after Meek). 533. Scaphiocrinus scalaris (after Meek). 534. Forbesiocrinus Wortheni (after Meek).

Among *Crinoids*, the *Cystids* no longer exist, for they passed out with the Silurian, but the *Blastoids* and *Crinids* (Fig. 528–535) increase in number and beauty. Also among free Echinoderms the Asteroids (Fig. 538) are more abundant, and Echinoids (Figs. 536 and 537), introduced in small numbers in the Devonian, are more nu-

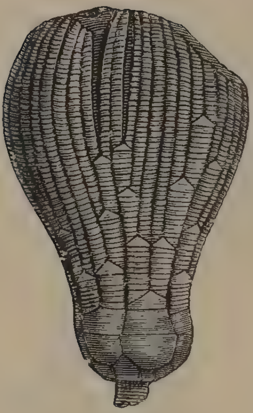


FIG. 535.

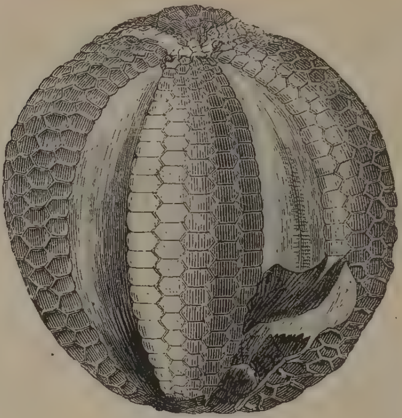


FIG. 536.

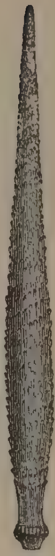


FIG. 537 *b*.

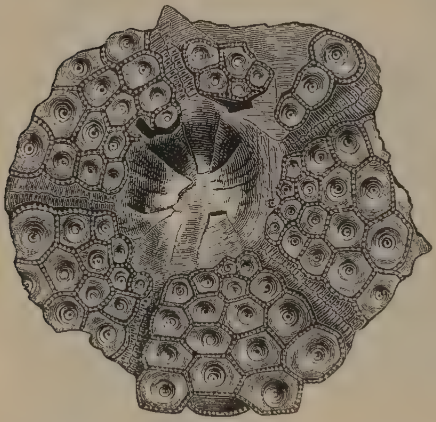


FIG. 537 *a*.

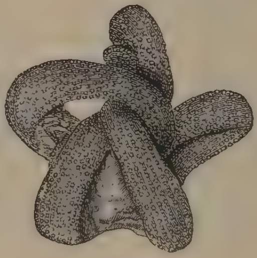


FIG. 538.

FIGS. 535-538.—ECHINODERMS OF THE CARBONIFEROUS AGE – *Crinid:* 535. Zeacrinus elegans (after Hall). *Echinoids and Asteroids;* 536. Oligoporus nobilis, × ½ (after Meek). 537. *a*, Archæocidaris Wortheni (after Hall); *b*, Spine of same, natural size. 538. Onychaster flexilis (after Meek).

merous here. Fig. 539 represents the distribution of these orders in time.

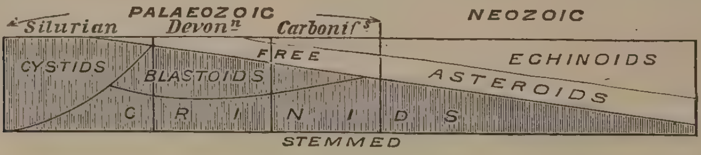


FIG. 539.—Diagram showing General Distribution of Echinoderms in Time: Shaded portion, stemmed; unshaded, free.

Among Brachiopods, the straight-hinged or square-shouldered kinds continue, but pass out almost wholly with this age.

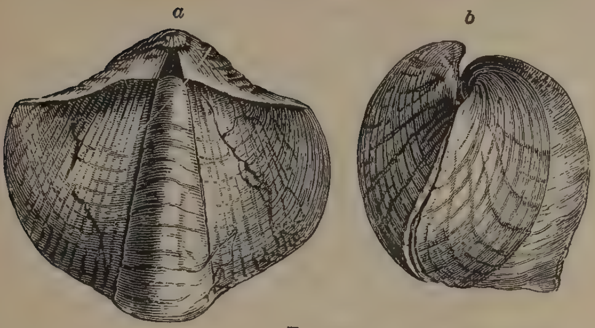
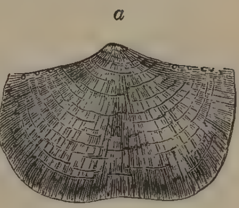


Fig. 540.



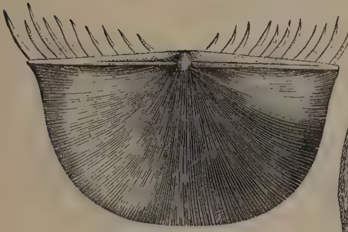


Fig. 541.

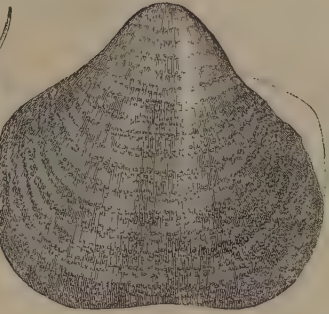


Fig. 542.

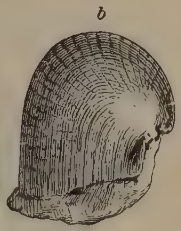


Fig. 543.

Figs. 540–543.—Carboniferous Brachiopods: 540. Spirifer plenus (after Hall); *a*, dorsal view; *b*, side view. 541. Chonetes Dalmaniana. 542. Productus punctatus (after Meek). 543. Productus mesialis (after Hall); *a*, ventral view; *b*, side view.

Land and fresh-water shells (Figs. 544–548) begin to appear first in the Coal-measures. The genus *Pupa*, a land air-breathing gasteropod, and the genus *Cyclas*, a fresh-water bivalve, and the genus *Cypris*,

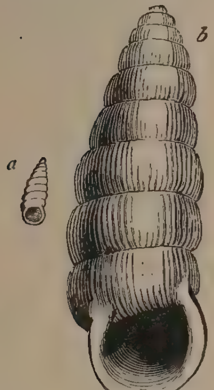


Fig. 544.

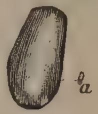


Fig. 545.

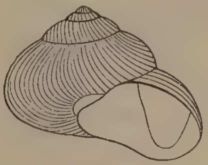


Fig. 547.

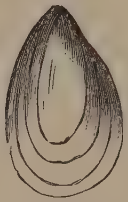


Fig. 546.

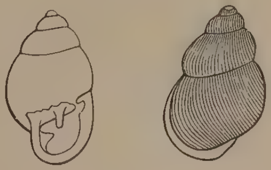


Fig. 548.

Figs. 544–548.—Carboniferous Land and Fresh-water Shells: 544. Pupa vetusta (after Dawson)—a Land-Shell; *a*, natural size; *b*, enlarged. 545. Cypris (after Dawson); *a*, natural size. 546. Naiadites (after Dawson). 547. Dawsonella Meekii (after Bradley). 548. Anthracopupa Ohioensis (after Whitfield).

a little crustacean bivalve, all of which are still represented by living species, are found. It would seem that evolution-changes, both progressive and differential, are more slow in fresh-water forms (White).

Of course, *marine* species, both Lamellibranchs and Gasteropods, are abundant. Some figures of these are given below.

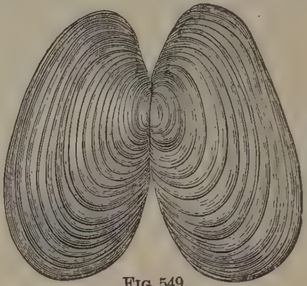


FIG. 549.

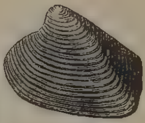


FIG. 552.

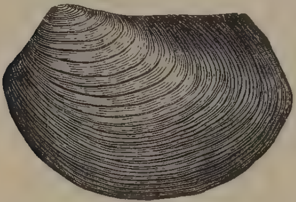


FIG. 550.

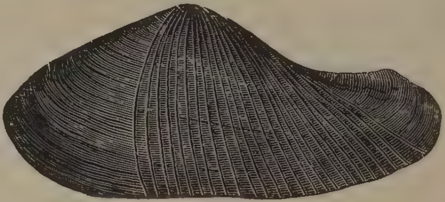


FIG. 551.

FIGS. 549–552.—CARBONIFEROUS LAMELLIBRANCHS (after Meek): 549. Solenomya anodontoides. 550. Allorisma ventricosa. 551. Allorisma pleuropistha. 552. Astartella Newberryi.

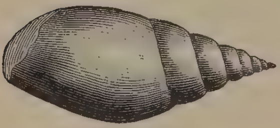


FIG. 553.

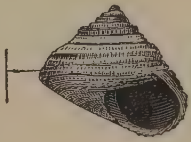


FIG. 554.

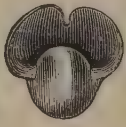


FIG. 556.

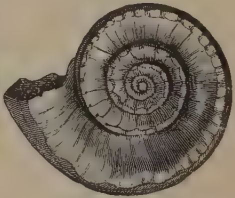


FIG. 555.

FIGS. 553–556.—CARBONIFEROUS GASTEROPODS (after Meek): 553. Macrocheilus Newberryi. 554. Pleurotomaria scitula. 555. Euomphalus subquadratus. 556. Bellerophon sublævis (after Hall).

Among *Cephalopods*, Orthoceratites still continue, but in diminished number, variety, and size. *Goniatites*, introduced in the Devonian, or even earlier in Europe, also continue, but both may be said to pass out with this age, although a few seem to pass into the Lower Triassic.

Trilobites and *Eurypterids* also continue ready to disappear at the end, but an advance in the Crustacean class is observed in the introduction here of *Limuloids* (king-crabs), Fig. 559, and of *Macrourans* —long-tailed Crustaceans (lobsters, crawfish, shrimps, etc.), Figs. 562 and 563. Here, then, we have two important steps in the progress of life. The gradual process of change may be clearly traced in the one, but not yet in the other. Although Limuloids are clearly differentiated first in the Carboniferous, yet transition forms may be traced even to

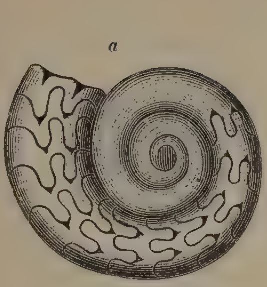


FIG. 557.

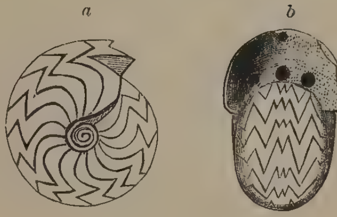


FIG. 558.

FIGS. 557, 558.—CARBONIFEROUS GONIATITES: 557. Goniatites Lyoni (after Meek); *a*, side view; *b*, end view. 558. Goniatites crenistria (European); *a*, side view; *b*, end view.

the Upper Silurian. If, with Packard, we divide Crustaceans into two groups—Palæo-carida and Neo-carida (old style and new style Crustaceans)—then Trilobites, Eurypterids, and Limuloids, belong to

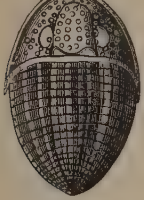


FIG. 560.

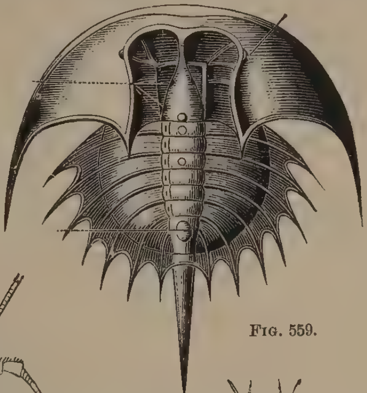


FIG. 559.

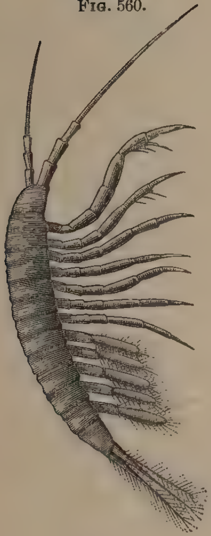


FIG. 561.

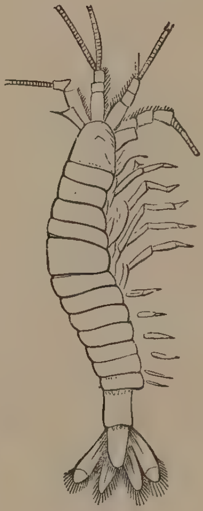


FIG. 562.

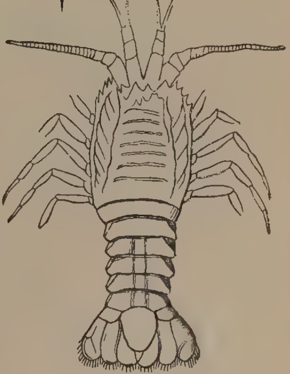


FIG. 563.

FIGS. 559-563.—CARBONIFEROUS CRUSTACEANS: 559. Euproöps Danæ (after Meek and Worthen). 560. Phillipsia Lodiensis (after Meek). 561. Acanthotelson Stimpsoni restored (after Packard). 562. Palæocarus typus (after Meek and Worthen). 563. Anthrapalæmon gracilis (after Meek and Worthen).

the Palæo-carida. That these were all derived from the Trilobite is shown by the transition forms 564 *a* and *b*, which must be compared with figures of Trilobites and Limulus previously given. As already seen (p. 337), the same view is confirmed by embryology. The genesis of the Neo-carida we do not know. They certainly did not come from the Palæo-carida, but probably from some early and low form of Crustaceans like Hymenocarus (Fig. 290, p. 312). If so, then the earliest pre-Cambrian Crustacea separated into two branches, (1) the Trilobites and (2) the Phyllocarids, both of which are found in the Cambrian. The Trilobites developed into Eurypterids and Limuloids, while the Phyllocarids barely held their own until the Trilobites had exhausted their vitality and were about to disappear, and then they developed into the Neo-carida or modern Crustacea (Walcott).

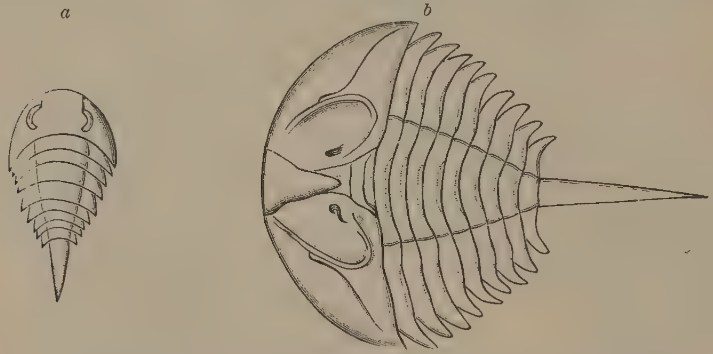


Fig. 564.—*a*, Palæoniscus aculeatus (after Nieskowski): a Eurypterid from Upper Silurian. *b*, Neolimulus falcatus (after Woodward): a Limuloid from Upper Silurian.

Insects now, for the first time, appear in considerable numbers and variety. As might be expected, these are associated with the abundant land vegetation of the Coal. Many of the principal orders are here represented, viz., Dragon-flies (Neuropters), Figs. 568 and 571; grasshoppers and cockroaches (Orthopters), Fig. 567; spiders and scorpions (Arachnids), Figs. 565 and 566; and centipeds (Myriapods), Figs. 570 and 570 *a*. It is noteworthy, however, that the three highest orders, viz., the butterflies (Lepidopters), the social insects, such as bees, ants, etc. (Hymenopters), and the flies (Dipters), are still wanting. These are not only the highest but also the flower-loving, honey-sucking orders. True flowering plants (Angiosperms) did not yet exist. Beauty and fragrance and sweetness were not yet characteristic of the reproduction of plants.

Recently immense numbers of Carboniferous insects have been found at Commentry and described by Brogniart. Among these are the largest insects known. One—a phasma (Fig. 571)—was about a foot long and twenty-six or twenty-eight inches across the extended wings. As already said (p. 347), all the Palæozoic hexapod insects belong to one order—the *Palæo-dictyoptera* of Scudder—a generalized type, connecting the three lower orders—Neuropters, Orthopters, and Hemipters—of existing insects; some approaching one and some another of these now widely separated orders.

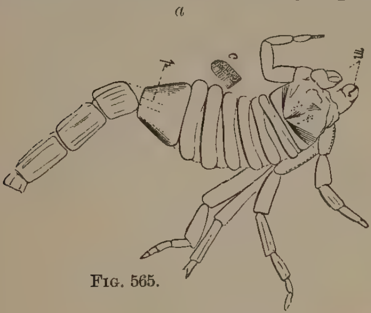


FIG. 565.

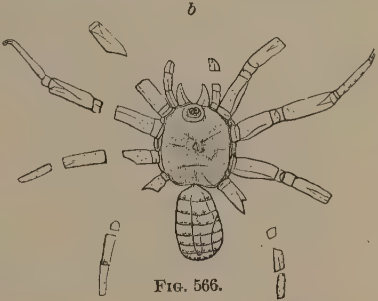


FIG. 566.

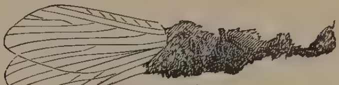
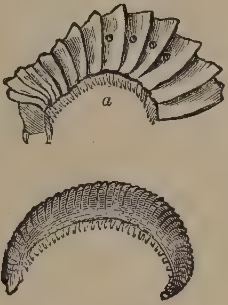


FIG. 568.



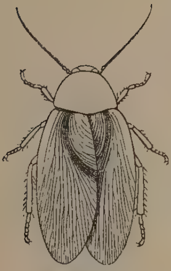


FIG. 567.

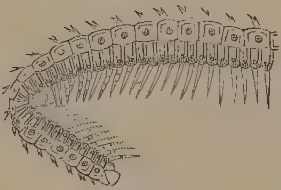


FIG. 569.

FIG. 570.

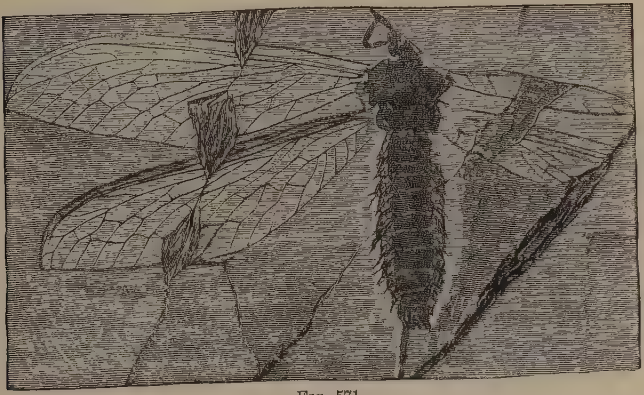


FIG. 571.

FIGS. 565-571.—CARBONIFEROUS INSECTS: 565. Eoscorpius carbonarius (after Meek and Worthen). 566. Anthrolycosa antiqua (after Beecher). 567. Blatta Helvetica, × ½, restored (after Heer). 568. Miamia Danæ (after Scudder). 569. Euphoberia armigera (after Meek and Worthen). 570. Zylobius sigillariæ (after Dawson). *a*, Anterior portion enlarged. 571. Corydaloides Scudderi, × ⅛ (after Brogniart).

In Palæozoic insects, according to Brogniart, we have the following generalized characters: 1. The three joints of the thorax were not yet consolidated. 2. There were three pairs of wings corresponding to the three pairs of legs, the anterior pair being small, almost rudimentary. 3. The pairs of wings were all alike diaphanous, the anterior pair being afterward hardened in many kinds, as in grasshoppers and beetles. 4. Tracheo-branchiæ were present on the sides of the abdomen.*

Vertebrates (Fishes).—The great Ganoids and Elasmobranchs continue in undiminished or even increased numbers, size, and variety. They are still the rulers of the seas. Of Elasmobranchs, one has been found with dorsal spine eighteen inches long, another with spine three inches broad and nine and a half inches long, although much of the point is broken off. Their teeth, too, are beginning to assume more of the character of true shark's-teeth. They are no longer wholly *Cestracionts* (Fig. 575), but also now *Hybodonts*, having teeth somewhat like modern sharks, but rounded on the edges (Figs. 576 and 577). In Fig. 578 we give a restoration by Sauvage of an early generalized form of shark. Among *Ganoids*, the well-protected but sluggishly-moving *Placoderms* have passed away, but the *Sauroids* continue in increased numbers and size. Bony, enameled *scales* of the Megalichthys and Holoptychius are found, two to three inches across; and jaws of the Holoptychius, a foot or more long, armed with Saurian teeth, two inches in length (Fig. 580). Also, as we approach the time for the appearance of Reptiles, some of these Sauroid fishes seem to

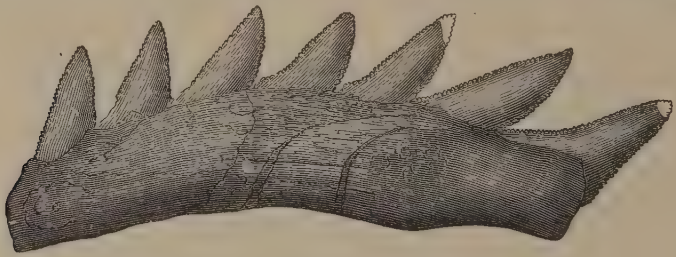


Fig. 572.

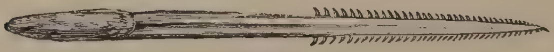


Fig. 573.

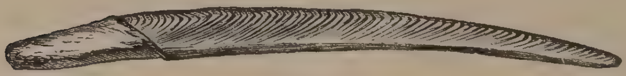


Fig. 574.

Figs. 572-574.—Carboniferous Fishes—*Elasmobranchs:* 572. Edestes minor (after Newberry). 573. Pleuracanthus—a Shark (after Nicholson). 574. Gyracanthus (after Nicholson).

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* Bull. Soc. de l'industrie minerale, vol. vii, p. 575.

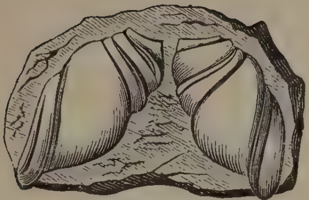

FIG. 575.

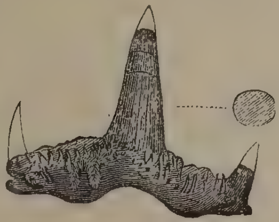

FIG. 578.

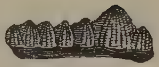

FIG. 577.

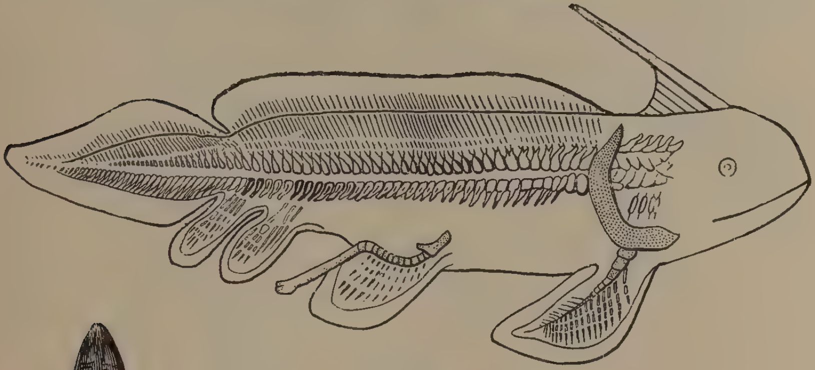

FIG. 576.

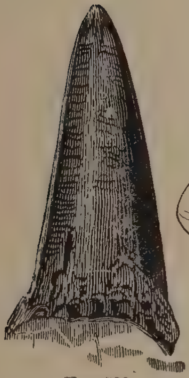

FIG. 580.

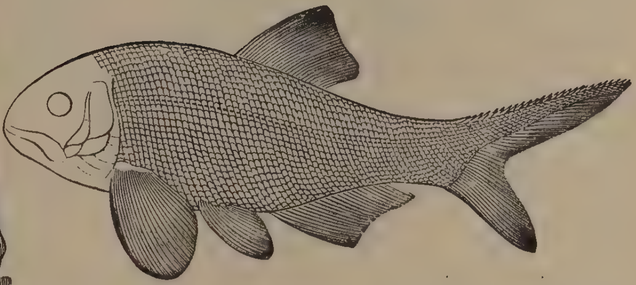

FIG. 579.

FIGS. 575-580.—CARBONIFEROUS FISHES—*Elasmobranchs:* 575. Cochliodus contortus. 576. Xenacanthus Dechenii, $\times \frac{1}{8}$ (after Cope), from the Coal-measures of France. 577. Orodus mammilare (after Newberry). 578. Cladodus spinosus (after Newberry). *Ganoids:* 579. Amblypterus macropterus. 580. Tooth of Holoptychius Hibberti, natural size.

become still more reptilian in character, while others become more *fish-like.*

Amphibians.—The first known appearance on the earth of air-breathing or land vertebrates was in this age, and, as might have been expected, in the lowest form, viz., *Amphibians.*

Amphibians were formerly classed as one of the *orders* of Reptiles then as a *sub-class;* but now they are recognized as a distinct *class* intermediate between Fishes and Reptiles, and approaching more nearly the former than the latter. True Reptiles are not certainly known to be represented in the Carboniferous. Amphibians are divided into four orders, viz.: 1. Tailless Amphibians (*Anoura*), such as frogs, toads, etc.; 2. Tailed Amphibians (*Urodela*), such as tritons, salamanders, sirens, etc.; 3. The rare snake-like forms (*Ophiomorpha* or *Gymnophiona*); and 4. *Labyrinthodonts.* Of these, only the Labyrinthodonts were represented in the Carboniferous. The other three orders still exist, but the last has been long extinct. The Labyrinthodonts were very large, often gigantic reptiles. They were most of them salamandriform, with long tails, weak limbs, and sluggish movement. Some were pisciform, and had paddles instead of feet.

We can only briefly describe a few representatives of the class, and draw some conclusions.

1. **Amphibian Footprints.**—In the sub-Carboniferous of Pennsylvania, near Pottsville, have been found *tracks* of a four-footed, crawling animal (*Sauropus primævus*), having thick, fleshy feet about four inches long, and making a stride of about thirteen inches. The impression of a dragging tail is also visible. The surface of the slab on which the tracks are found is marked with distinct ripple-bars and rain-prints. "We thus learn," says Dana, "that there existed in the region about Pottsville, at that time, a mud-flat on the border of a body of water; that the flat was swept by wavelets, leaving ripple-marks; that the ripples were still fresh when a large amphibian walked across the place; that a brief shower of rain followed, dotting with its drops the half-dried mud; that the waters again flowed over the flat, making new deposits of detritus, and so buried the records." *This is the earliest known land-vertebrate.*

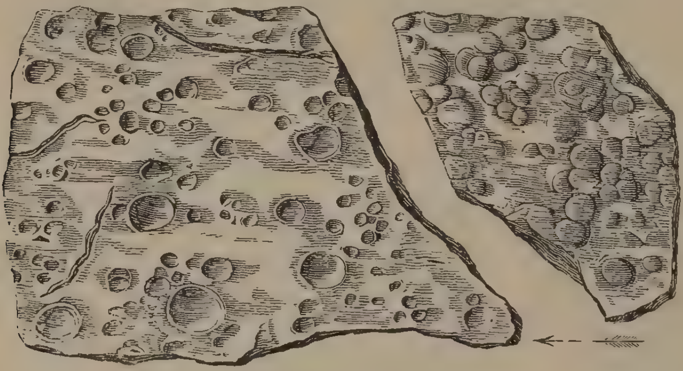

FIG. 581.—Fossil Rain-prints of the Coal Period.

Similar tracks have also been found in the Coal-measures of Pennsylvania, on a slab affected with *sun-cracks* (Fig. 582). The reptile had evidently walked on the cracked and half-dried mud at low tide.

Tracks have also been found in the Coal-measures of Illinois, Indiana, Kansas, and Nova Scotia, and in the latter region beautiful specimens of rain-prints (Fig. 581). In Fig. 583 we give also foot-prints found in the coal-measures of Kansas.

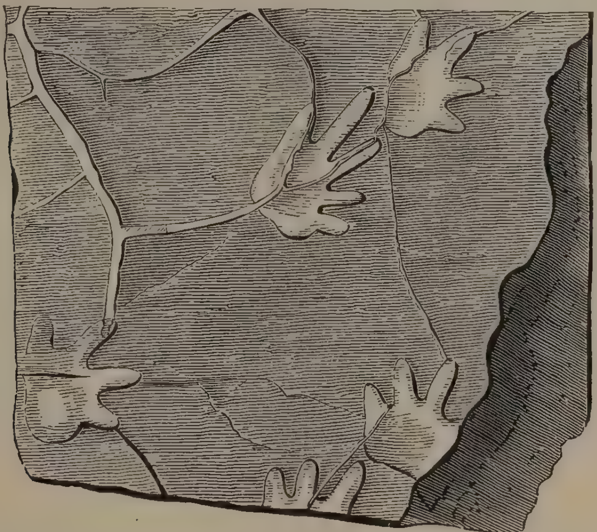

FIG. 582.—Slab of Sandstone with Amphibian Footprints, from Coal-measures of Pennsylvania, × $\frac{1}{8}$.

There can be little doubt that the reptiles making the tracks mentioned above were *Labyrinthodonts*.

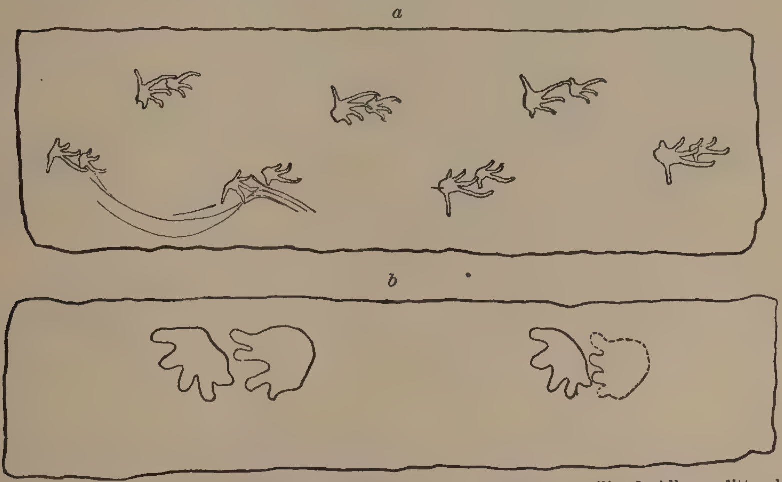

FIG. 583.—Footprints in Coal-measures of Kansas, × $\frac{1}{12}$: *a*, Dromopus agilis; *b*, Allopus littoralis (after Marsh).

2. **Dendrerpeton.**—In the Coal-measures of Nova Scotia have been found quite a number of small amphibians, belonging to several genera. Among these one is especially interesting, on account of the conditions under which it seems to have been preserved. It is called the *Dendrerpeton*—tree-reptile (Fig. 584), because it was found by Dawson and Lyell in sand-stone, filling the hollow stump of a Sigillaria (Fig. 585), along with another small species of amphibian, a number of land-shells —pupa, etc. (Fig. 544, p. 409), and a myriapod (Fig. 570, p. 413). The Sigillaria possessed a thick, strong bark, which was more resistant of decomposition than the cellular interior. Stumps of these trees are often found, consisting only of coaly bark filled with sandstone, evidently deposited within the hollow. These sands are rich repositories of organic remains. We can easily imagine the circumstances under which the Dendrerpeton was preserved. A dead Sigillaria tree, rotted to the base and only its hollow stump remaining, stood on the margin of a coal-swamp; river-floods filled the stump with sand; in the stump lived and perished a Dendrerpeton; or else, more probably, the dead body of the reptile, together with shells and other organic remains, was floated into the hollow stump and buried there. This amphibian was probably a Labyrinthodont, but with strong alliances with true reptiles, especially Lacertians.

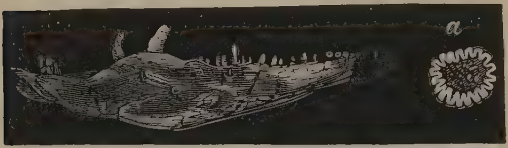

Fig. 584.—Jaw of Dendrerpeton Acadeanum, and Section of Tooth, enlarged (after Dawson).

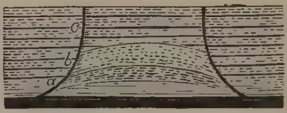

Fig. 585.—Section of Hollow Sigillaria Stump, filled with Sandstone (after Dawson).

3. **Archegosaurus** (*Primordial Saurian*).—In the Bavarian Coal-measures has been found the almost perfect skeleton of an animal about three and a half feet long, which combines in a remarkable degree the characters of *Amphibians* with those of *Ganoid Fishes.* It seems to have been a Labyrinthodont Amphibian, with general form and structure adapted for a purely aquatic life. It had, certainly in the early stages of its life, probably throughout life, both gills and lungs, and therefore, like all the Amphibians of the present day at this stage, or like Perennibranchiate Amphibians throughout life, breathed both air and water. The locomotive organs were paddles, adapted for swimming, not for walking. The body was covered with imbricated *ganoid scales* (Fig. 586, *A*), and the head with *ganoid plates.* The structure of the teeth (*B*) was also ganoid. The bodies of the vertebræ were not ossified nor even cartilaginous, but retained the early embryonic, fibrous condition of a *notochord.* It was apparently a connecting link

between the lowest Perennibranchiate Amphibians and the Sauroid Fishes (Owen), with, perhaps, some alliances with the marine Saurians which afterward appeared. It was so distinct from other Labyrinthodonts that Prof. Owen puts it in a distinct order which he calls *Ganocephala*. The skeleton of this animal is given above (Fig. 586) with the limbs (*C* and *D*) and jaw (*E*) of a Proteus—a perennibranchiate amphibian—for comparison.

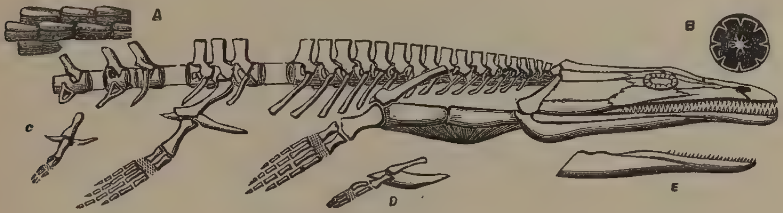

Fig. 586.—Archegosaurus.

4. **Eosaurus.**—In the Coal-measures of Nova Scotia, in 1861, Prof. Marsh found the vertebræ of what he thinks, with some reason, was a marine Saurian; an order which is largely developed in the Mesozoic. If so, it would be the earliest known reptile. But as only the bodies of a few vertebræ have been found, and as the bi-concavity of these is the chief evidence of marine Saurian affinity and as bi-concavity also exists among Labyrinthodonts, Huxley believes this was also a Labyrinthodont. There is, however, still some doubt as to the true affinity of this animal. The size of some of the vertebræ was two and a half inches in diameter, indicating an animal of gigantic dimensions.

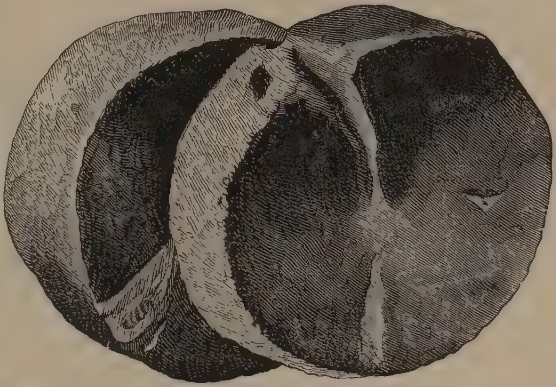

Fig. 587.—Two Vertebræ of Eosaurus Acadianus (after Marsh).

Many other genera have been described by authors both in Europe and America. Among these, Baphetes, Raniceps, Hylerpeton, Hylonomus, and Amphibamus from America, and Anthracosaurus, Ophiderpeton, and Apateon from Europe, are best known. The Baphetes and the Anthracosaurus attained gigantic size.

Very recently a large number (thirty-four species referable to seventeen genera) of small Amphibians have been brought to light by the

Ohio Survey, and described by Cope. These are all, or nearly all, Labyrinthodonts (*Stegocephali*, Cope). Some of them have the usual broad heads of Amphibians, but a large number are remarkable for their long, limbless, snake-like forms and pointed heads. These are evidently among the lowest forms of Amphibians, and have strong affinities also with Ganoid fishes. Figs. 588 and 589 represent two of the Ohio Amphibians.

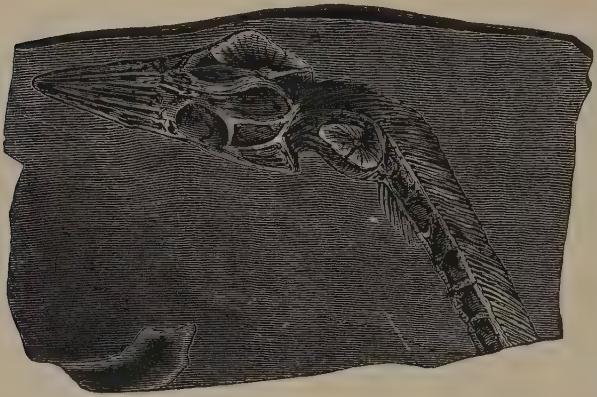

FIG. 588.—Ptyonius (after Cope).

Some General Observations on the Earliest Land Vertebrates.—With the possible exception of the Eosaurus, all the air-breathing vertebrates of the Carboniferous were Labyrinthodonts. They are so called on account of the extraordinary labyrinthine structure of their teeth, produced by the intricate infolding of the surface and of the cavity. The same structure is observed in Ganoid teeth, but in a far less degree. The simple infoldings of Ganoids (Fig. 453, p. 355) become intricate in Labyrinthodonts (Fig. 590).

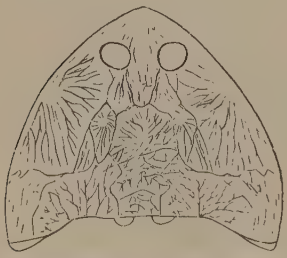

FIG. 589.—Tuditanus radiatus, × ½ (after Cope).

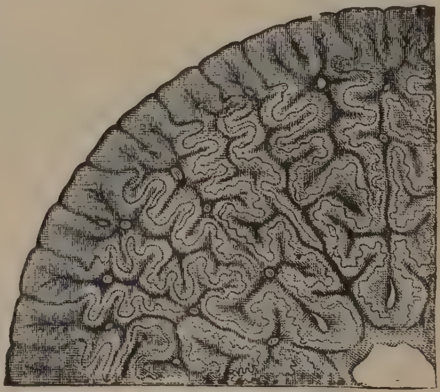

FIG. 590.—Section of Tooth of a Labyrinthodont.

The Labyrinthodonts were probably the most complete example of a connecting type which has yet been discovered. First, they were true Amphibians in the strictest sense, having all of them in the early stages of their life—some throughout life—both lungs and gills, and thus connecting water-breathers with air-breathers. Again, they were very different from the slimy-skinned Amphibians of the present day, in being covered, at least partly, with bony plates or scales over the body, and with closely-fitting bony plates over the head. Again, they differed wholly from the present Amphibians in having jaws thoroughly armed with very large and powerful teeth, the structure of which is labyrinthine. All of these characters connected them with Sauroid fishes which preceded them, and the great Saurian reptiles which succeeded them. Finally, they seemed to possess also characters connecting them with several orders of subsequently-existing reptiles. In the Labyrinthodonts and Sauroid fishes we can almost find the point of separation of the two great branches, Amphibian and Fish, of the vertebrate stem; and in the former the commencing differentiation of the several orders of Reptiles. All the earliest Amphibians had persistent notochord (Cope).

Some General Observations on the Whole Palæozoic.

We have defined geology as the history of the evolution of the earth. *Evolution*, therefore, is the central idea of geology. It is this idea alone which makes geology a distinct science. This is the cohesive principle which unites and gives significance to all the scattered facts of geology—which cements what would otherwise be a mere incoherent pile of rubbish into a solid and symmetrical edifice. It seems appropriate, therefore, that at the end of the long and eventful Palæozoic era we should glance backward and briefly recapitulate the evidences of progressive change (evolution), physical, chemical, and vital.

Physical Changes.—The Palæozoic era opened on this continent with a V-shaped mass of land—the Archæan area—to the north; also, a land-mass of Archæan rocks, of unknown shape and extent, on the eastern border, and probably some islands and masses of larger extent in the Basin and Rocky Mountain regions. This condition of things is represented on the map on page 303. Throughout the Palæozoic era there was an accretion of land to this nucleus by upheaval of contiguous sea-bottoms; a development of the continent *southward* (and perhaps northward) from the northern area, and both eastward and westward from the eastern border area, until at the end of the Palæozoic the eastern half of the continent included *certainly* all the Archæan, Silurian, Devonian, and Carboniferous areas shown on the map on page 302, and probably also some on the eastern border of the eastern Archæan area, which was subsequently covered by the sea, and is therefore now concealed by more recent deposits. The loss of Palæozoic land on the *eastern* border probably took place during the *Appalachian revolution.* In the Rocky Mountain region the development was probably less steady. Unconformity of Carboniferous on Silurian strata shows extensive land areas there during Devonian times. Thus it is seen that the continent was already sketched in the beginning of the Palæozoic, and the process of development went on during that era, so that at the end the outlines of the continent were already unmistakable. We shall trace the further development hereafter.

Chemical Changes.—Progressive changes in chemical conditions are no less evident. At first—i. e., before the Archæan era—before the existence of life on the earth—the atmosphere, as shown by Hunt,* was loaded with carbonic acid, representing all the *carbon and carbonates* in the world; with sulphuric acid representing all the *sulphur and sulphates;* with hydrochloric acid representing all the *chlorides;* and with aqueous vapor representing all the *water* on the earth. Of course, such a condition rendered life impossible. From this primeval atmosphere, by cooling, the strong acids were first precipitated with the water; and afterward more slowly the carbonic acid, by the action of this acid upon the primeval silicates, with the formation of carbonates, especially limestone. All limestones, therefore, represent so much carbonic acid withdrawn from the air. This withdrawal proceeded, through the whole Archæan, Cambrian, Silurian, and Devonian. During the Carboniferous, the purification of the air was accelerated by the growth of vegetation and its preservation as coal, as already explained, pages 370 and 397. In this method of withdrawal the oxygen of the carbonic acid is returned, and the air becomes more oxygenated.

Progressive Change in Organisms.—Corresponding with these changes, physical and chemical, it is natural to expect changes in species, genera, families, etc., of organisms: and such we find. The law of *continuance* or *geological range* of species, genera, families, orders, is very similar to that of *extent* or *geographical range* of the same groups; i. e., the laws of distribution in *time* are similar to those of distribution in *space.* The *period of continuance* (range in time) of species is, of course, less than that of genera (because the genus is continued in other species of the same genus), and that of genera less than that of families, etc. According to Prof. Hall, there have been in the Silurian and Devonian ages alone at least *thirty almost complete changes of species.* The changes of genera are, of course, much less numerous, and those of families still less than those of genera. These general laws may be illustrated by any Palæozoic order; but I select the order of Trilobites, because they are very numerous, very diversified, and well studied, and because they *came in* with the Palæozoic, *continued* throughout the whole era, and then passed away for ever.

The diagram (Fig. 591) illustrates these laws in the order of Trilobites. It is seen that this order continues through the whole era, commencing in small numbers, reaching its highest development in the Lower Silurian, and declining to the end. But the *families* are changed several times. Six groups are given, to show how they come and go successively. If we should attempt the distribution of *genera*, the changes would be much more numerous, and of *species* still more so. In the lower portion of the diagram we have attempted to show in a very general way how the distribution of species of Calymene and Acidaspis might be represented.

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* Geological Essays, p. 40 *et seq.*

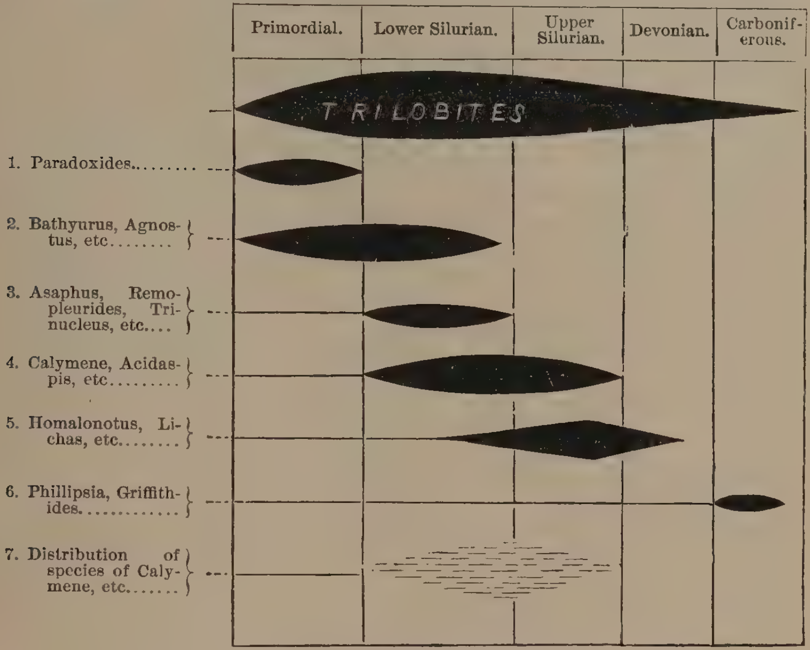
Primordial.
Lower Silurian.
Upper Silurian.
Devonian.
Carboniferous.
TRILOBITES
1. Paradoxides
2. Bathyurus, Agnostus, etc.
3. Asaphus, Remopleurides, Trinucleus, etc.
4. Calymene, Acidaspis, etc.
5. Homalonotus, Lichas, etc.
6. Phillipsia, Griffithides.
7. Distribution of species of Calymene, etc.

Fig. 591.—Diagram illustrating Distribution of Families, etc., in Time.

General Comparison of the Fauna of Palæozoic with that of Neozoic Times.—The changes above explained were gradual; but at the end of the Palæozoic there occurred a more rapid and revolutionary change, and the greatest which has ever occurred in the history of the organic kingdom. As human history is primarily divided into Ancient and Modern, so the whole history of the earth may be properly divided into *Palæozoic* and *Neozoic* times. We wish to contrast broadly the faunæ of these two great divisions of time. In the diagram on next page, the vertical line represents the dividing line between the *old* and the *new* time-world. In this country it is appropriately called the Appalachian revolution. On the left is the Palæozoic, on the right the Neozoic. When families or orders of animals are placed on one or the other side without mark, it means that they are the *only kind* of the contrasted families found on that side, or nearly so. If the orders or families so placed are marked with the sign +, it means that they are the *predominant kinds*; if + +, greatly so. For example, among Ce-

Palæozoic times		..Neozoic times.
	RADIATA.	
	Corals.	
+ Quadripartita		..Sexpartita +.
	Echinoderms.	
+ + Stemmed, or Crinoids		..Free, or Echinoids and Asteroids + +.
	Crinoids.	
+ Armless, or simple arms		..Plumose arms.
	MOLLUSKS.	
	Bivalves.	
+ Brachiopods		..Lamellibranchs + +.
	Brachiopods.	
+ Square-shouldered		..Sloping-shouldered.
	Lamellibranchs.	
+ Unsiphonated		..Siphonated +.
	Gasteropods.	
Marine		..Land, fresh-water, and marine.
	Marine.	
Unbeaked—Herbivorous		..Beaked—Carnivorous +.
	Cephalopods.	
Shelled, or Tetrabranchs		..Naked, or Dibranchs + +.
	Shelled.	
+ Straight		..Coiled.*
Orthoceratites.		
	N—a—u—t—i—l—o—i—d—s.	
	Goniatites.	
		Ceratites.
		Ammonites.
	ARTHROPODA.	
	Crustacea.	
Palæocarida		..Neocarida +.
Trilobites.		
Eurypterids.		
	Limuloids.	
		Macrourans.
		Brachyourans.
	VERTEBRATA.	
	Fishes.	
Heterocercals		..Homocercals +.
Ganoids and Elasmobranchs..		................Teleosts +.
	Elasmobranchs.	
Cestracionts.		
Hybodonts		....
		Squalodonts +.
	Reptiles.	
Amphibians		..True Reptiles +.

* Baculites of the Cretaceous are an exception.

phalopods, the Tetrabranch, or shelled family, are the *only* kinds found in the Palæozoic; in the Neozoic, both families exist, but the Dibranchs or naked ones vastly *predominate.*

General Picture of Palæozoic Times.

Perhaps it is not inappropriate to group some of the more important facts in a very brief outline-picture of Palæozoic times. We must imagine, then, *wide* seas and *low* continents of *small extent;* a hot, moist, still air, loaded with carbonic acid, stifling and unsuited for the life of warm-blooded animals. If an observer had walked along these early beaches he would have found cast up, in great numbers, the shells of Brachiopods; clinging to the rocks and hiding away among their hollows, instead of sea-urchins and star-fishes and crabs, he would have found crinoids and trilobites. In the open sea he would have found as rulers, instead of whales and sharks and teleosts and cuttle-fish, huge cuirassed Sauroids and the straight-chambered Orthoceras. Turning to the land, he would have seen at first only desolation; for there were almost no land-plants until the Devonian, and almost no land-animals until the Coal. During the Coal there were extensive marshes, overgrown with great trees of Sigillaria, Lepidodendron, and Calamites, whose dense underbrush of Ferns, inhabited by insects and amphibians; no umbrageous trees, no fragrant flowers or luscious fruits, no birds, no mammals. These "dim, watery woodlands" are flowerless, fruitless, songless, voiceless, except the occasional chirp of the grasshopper. If the observer were a naturalist, he would notice also the complete absence of modern types of plants and animals—it would be like another world.

Appalachian Revolution.—This long dynasty was overthrown, this reign of Fishes and Amphibians ended, the physical conditions described above were changed, and the whole fauna and flora destroyed or transmuted by the Appalachian revolution. Not a single species is known to have crossed this line. At the end of the Palæozoic, the sediments which had been so long accumulating in the Appalachian region at last yielded to the slowly-increasing horizontal pressure, and were mashed and folded and thickened up into the Appalachian chain, and the rocks metamorphosed. In America, this chain is the monument of the greatest revolution which has taken place in the earth's history. At the same time the Acadian range of East Canada and the Ouachita range of Arkansas seem to have been formed (Dana). At the same time also great changes took place in the West. The Utah basin region was upheaved to form land, the Nevada basin region sank and became sea-bottom, and the Pacific shore-line was transferred eastward to the 117th meridian about Battle Mountain. In other words, the Basin region Palæozoic continent was transferred eastward its own breadth to form the Basin region Mesozoic continent (King). Similar and very extensive changes in physical geography must have taken place in other portions of the globe, otherwise we can not account for the enormous changes in physical conditions and fauna and flora. Many of these have been traced, but we can not yet trace them as clearly as in America. The greatest of these and one of the greatest in the history of the earth was the formation of a great southern continent (Gondwana Land) connecting with South America, South Africa, and Australia. We shall have occasion to mention this again.

Transition from the Palæozoic to the Mesozoic—Permian Period.

The Permian a Transition Period.—The Palæozoic era was closed and the Mesozoic inaugurated by the Appalachian revolution. All the great revolutions in the earth's history are periods of oscillations. Such oscillations produce unconformity. They also produce changes of climate, and therefore of fauna and flora. We find, therefore, that the Mesozoic rocks are universally, or nearly universally,* unconformable on the Carboniferous; and, corresponding with this unconformity, there is a wonderful change in fauna and flora—a change the greatness of which we have attempted to show in the contrast on the previous page. Now, the older geologists regarded this change as one of instantaneous destruction and recreation, because they took no account of a lost interval. But we have already shown (pp. 188, 305) that in all cases of unconformity there *is* such a lost interval, which in some cases is very large. In order to account for the very great change in the organic world, it is only necessary to suppose that periods represented by general unconformity are *critical* periods in the earth's history—periods of rapid change in physical geography, climate, and therefore of rapid change in fauna and flora, by the passing out of old types and the differentiation of new types. Unfortunately, in the earth's history as in human history, it is exactly these critical periods—these periods of change and revolution—the record of which is apt to be lost. In both histories, too, this is truer the farther back we go. Of the long interval between the Archæan and Palæozoic, not a leaf of record has yet been recovered with any certainty; but of the interval now under discussion many leaves of record have been recovered. These have been bound together in a separate volume or chapter and called the *Permian*. I shall regard the Permian, therefore, as essentially a *transition period;* its rocks were deposited during the period of commotion; its fossil types are in a state of change, though more nearly allied to the Palæozoic. Among the great oscillations which occurred during this time is that already referred to on the previous page. We have good evidence, especially from Permian plants, that there existed at this time a great continental land-mass connecting South America, South Africa, Australia, and South India with one another and all with Antarctica. This hypothetical continent has been called by Suess *Gondwana Land.*

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* In the Rocky Mountain region there seems to be complete conformity in some places. (King, Fortieth Parallel Survey, vol. i, p. 266.)

From what has just been said, it will be anticipated that the unconformity of the Mesozoic on the Palæozoic sometimes takes place between the lowest Mesozoic and the Permian, and sometimes between the Permian and the Coal. The Permian, therefore, is sometimes conformable with the Coal, as, e. g., in this country, sometimes conformable with the Triassic, as in England. It thus allies itself stratigraphically sometimes with the Palæozoic, sometimes with the Mesozoic. Paleontologically it is always more allied to the Palæozoic. The English section, and the history of opinion concerning it, admirably illustrate this point. Fig. 592 is an ideal section through the Devonian, the Coal and Triassic (Lower Mesozoic) of England. Lying unconformably on the eroded surface of the Coal, *b*, there is seen a continuous and perfectly conformable series of strata, *a*. This series, moreover, is lithologically characterized throughout, especially the lower part, by frequent alternations of Red sandstones, and therefore has been called *New Red* sandstone, to distinguish it from the Devonian, which is often called Old Red sandstone. It is further distinguished throughout especially the upper part, by variegated shales, and therefore called altogether *Poikilitic* group. It is also distinguished throughout by the presence of salt, and therefore called the *Saliferous* group. Here, then, there were the strongest reasons for regarding the whole as one group, distinctly separated by unconformity from the underlying Coal. The upper part of this continuous series contained undoubted Mesozoic fossils. The line of unconformity was, therefore, naturally believed to be the line between Palæozoic and Mesozoic. Unfortunately, the lower portion is very barren of fossils, and this means of correcting the stratigraphic conclusion was at first nearly wanting. When fossils were discovered in sufficient numbers, however, they showed a greater alliance with the unconformable Coal below than with the conformable strata above. Thus, if we make the division between Palæozoic and Mesozoic on stratigraphical grounds, we would find it between the Coal and the overlying strata; while, if we make it on paleontological grounds, we would have to draw the line through the midst of the conformable strata, *a*, giving one half to the Palæozoic and the other

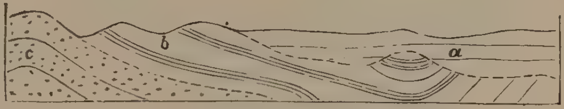

FIG. 592.—(After Lyell.)

half to the Mesozoic. The lower Palæozoic half is called the *Permian.**

As a broad general fact, therefore, the great commotion which is called the Appalachian revolution took place, or commenced to take place, at the end of the Coal period. But the fauna and flora were not immediately exterminated, but struggled on, maintaining, as it were, a painful existence, under changed conditions, themselves meanwhile changing, until complete and permanent harmony was re-established with the opening of the Mesozoic. If we may use an illustration, the Appalachian revolution was the death-sentence of Palæozoic types, but the sentence was not instantly executed. This transition period, between the sentence and the execution of Palæozoic types, is the Permian.

It is well here to draw attention to the fact of this great change of organisms, the greatest in the whole history of the earth, taking place *in the midst of conformable strata* (Fig. 592, *a*). Evidently the change must have been comparatively rapid.

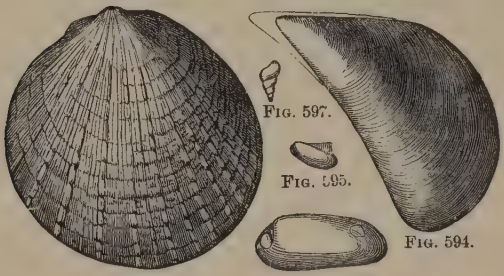

Fig. 597. Fig. 595. Fig. 594. Fig. 593. Fig. 596.

Figs. 593–597.—American Permian Fossils (after Meek): 593. Eumicrotis Hawni. 594. Myalina Permiana. 595. Bakewellia parva. 596. Pleurophorus subcuneatus. 597. A Gasteropod.

We have given the history of change of opinion in regard to the English section (Fig. 592), because it is a type of many discussions and changes which have occurred and will still occur in geological opinion.

Area in the United States.—The Permian has been found in the United States, in Kansas, bordering on, and conformable with, the coal of that region (map, p. 302); also in New Mexico and Western Texas, and probably also overlying the coal of Illinois (Cope). It gradates so completely into the upper Coal-measures that no attempt has been made to separate them in the map. Until recently nothing of interest has been found in the American Permian except a few shells (Figs. 593–597), but now a considerable number of fishes, amphibians, and reptiles are known.

An elementary treatise like this must dwell mainly on *culminating* periods, and their characteristic forms; and yet to the philosophic student it is the *transitional* forms and periods which are the most inter-

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* In Germany it is closely allied stratigraphically with the Triassic, and therefore by many put in the Mesozoic, and called *Dyas*.

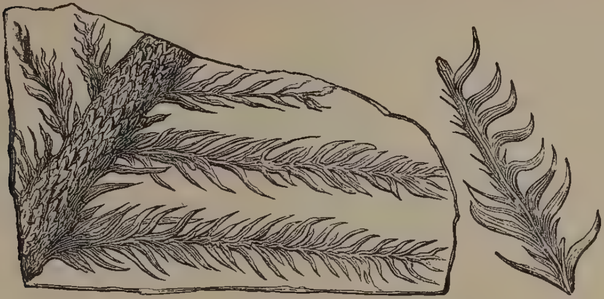

FIG. 598.

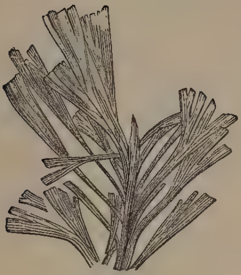

FIG. 599.

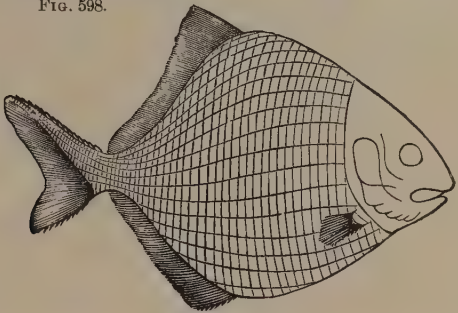

FIG. 600.

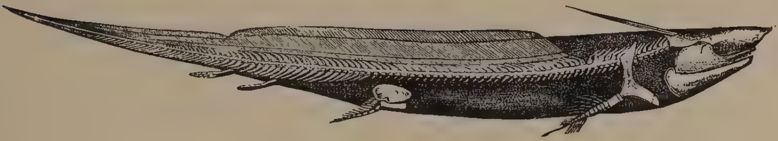

FIG. 601.

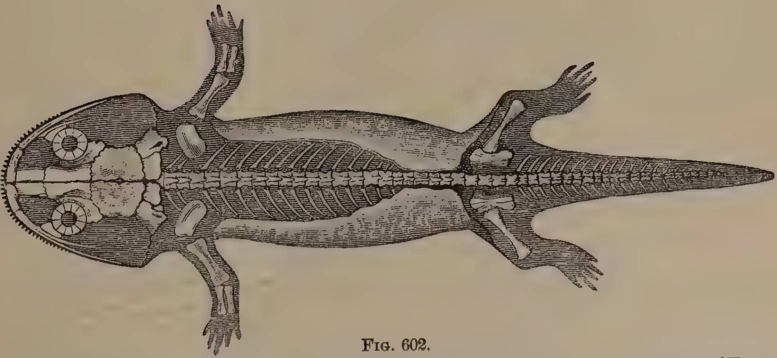

FIG. 602.

FIGS. 598–602.—EUROPEAN PERMIAN FOSSILS: *Plants:* 598. Walchia piniformis (Permian of Europe). 599. Ginkgophyllum. *Fishes:* 600. Platysomus gibbosus (Permian of Europe). 601. Pleuracanthus parellelus, restored (after Fritsch). *Reptile:* 602. Limnerpeton laticeps, natural size (after Fritsch).

esting. The Permian is pre-eminently such a transitional period, and contains many transitional forms. In it we have a passing away of

Palæozoic types, a coming in of Mesozoic types, and a co-existence of the two side by side. The change from the one to the other, therefore, was not sudden and by exterminations and recreations, but gradually by extinction of some old forms and modification of others into new forms; and *all the new forms were thus derived.* Under the influence of changing conditions, the more specialized and rigid forms became extinct, while the more generalized and plastic forms gave rise to modified descendants perhaps in several directions.

The main features of the Permian life, therefore, were: 1. A lingering of coal types of plants, such as the Lepidodendrids and Calamariæ, and many genera of Ferns, but extinction of Sigillarids and increase and advance of Conifers to more varied and modern forms, such as Walchia, Ginkgophyllum, etc. (Figs. 598, 599). 2. A lingering of Orthoceratites, square-shouldered Brachiopods, such as Productus and Spirifer, and perhaps of Goniatites, but complete extinction of Trilobites and Eurypterids. 3. A continuance of Ganoids, but under more modern forms (Figs. 600, 601). 4. Amphibians continue in the form of Labyrinthodonts (Stegocephali of Cope), of which some are very modern in form (Fig. 602), but *true reptiles* are introduced in considerable numbers. These first reptiles, as might have been expected, are wonderfully generalized in structure. They connect, on the one hand, with Amphibians, from which they were derived, and, on the other, with the lowest Mammals, to which they gave origin. On account of this connection with Mammals, Cope has called them *Theromorphs* (beast-like). We shall speak of these again under the Trias, where they are more abundant. Thus, then, we have at this time, Stegocephali, connecting Ganoid fish with reptiles, and Theromorphs, connecting Amphibians with Mammals. This is shown in the following schedule:

$$\begin{array}{l} \\ \text{Theromorphs}\ldots\ldots \\ \text{Stegocephali}\ldots\ldots \\ \\ \end{array}\left\{\begin{array}{l} \text{Monotreme Mammals.} \\ \left.\begin{array}{l}\text{Reptiles.}\\ \text{Amphibians.}\end{array}\right. \\ \end{array}\right. \ldots\left\{\begin{array}{l}\text{Reptiles.}\\ \text{Amphibians.}\\ \text{Fishes.}\end{array}\right.$$

CHAPTER IV.

MESOZOIC ERA—AGE OF REPTILES.

The Palæozoic era, we have seen, was very long, and very diversified in dominant types, of both animals and plants. It was during this long era that originated nearly all the great branches, and even subbranches, of the organic kingdom. We have during this era, therefore, three very distinct ages: an age of Invertebrates, an age of Fishes, and an age of Acrogens and Amphibians. The Mesozoic was far less long and far less diversified in dominant types. It consists of only one age, viz., the age of Reptiles. Never in the history of the earth, before or since, did this class reach so high a point in numbers, variety of form, size, or elevation in the scale of organization.

General Characteristics.—The general characteristics of the Mesozoic era are the *culmination of the class of Reptiles* among animals, and of *Cycads* among plants, and the *first appearance of Teleosts* (common osseous fishes), *Birds*, *Mammals* among animals, and of *Palms* and *Dicotyls* among trees.

Subdivisions.—The Mesozoic era is divided into three periods, viz.: 1. *Triassic*, because of its threefold development where first studied in Germany; 2. *Jurassic*, because of the splendid development of its strata in the Jura Mountains; 3. *Cretaceous*, because the chalk of England and France belongs to this period.

Mesozoic Era.
3. **Cretaceous period.**
2. **Jurassic period.**
1. **Triassic period.**

In this country the Triassic and Jurassic are not so distinctly separable as they are in Europe, nor as they are from the Cretaceous. They form, in fact, one series, and if the Mesozoic had been studied first in this country, the whole would probably have been divided into only two periods. We shall therefore speak of the Mesozoic of this country as consisting of two periods, viz., the *Jura-Trias* and the Cretaceous. On account of their fuller development in Europe, it will be best to speak, first, of the Triassic *generally*, then of the Jurassic generally, taking our illustrations mainly from European sources, and then of the Jura-Trias in America. Also, on account of the comparative poverty of the Trias in organic remains, we will dwell much less on this period than on the subsequent Jurassic; for in this latter period culminated all the distinctive characters of the Reptilian age.

Section 1.—Triassic Period.

As already stated, the Triassic strata are nearly always unconformable with the Coal, and the period opens with a fauna and flora wholly and strikingly different from the preceding. In many places, however, there is found an intermediate series, the Permian, sometimes conformable with the Coal and unconformable with the Trias, sometimes conformable with the Trias and unconformable with the Coal. Its fauna and flora are also to some extent intermediate, though more nearly allied to those of the Coal. The explanation of this has already been given.

Subdivisions.—The subdivisions of the Triassic rocks and period in several countries are given below.

GERMAN.	FRENCH.	ENGLISH.
3. Keuper.	Marne irisée.	Variegated marl.
2. Muschelkalk.	Muschelkalk.	Wanting.
1. Bunter Sandstein.	Grès bigarré.	Upper New Red sandstone.

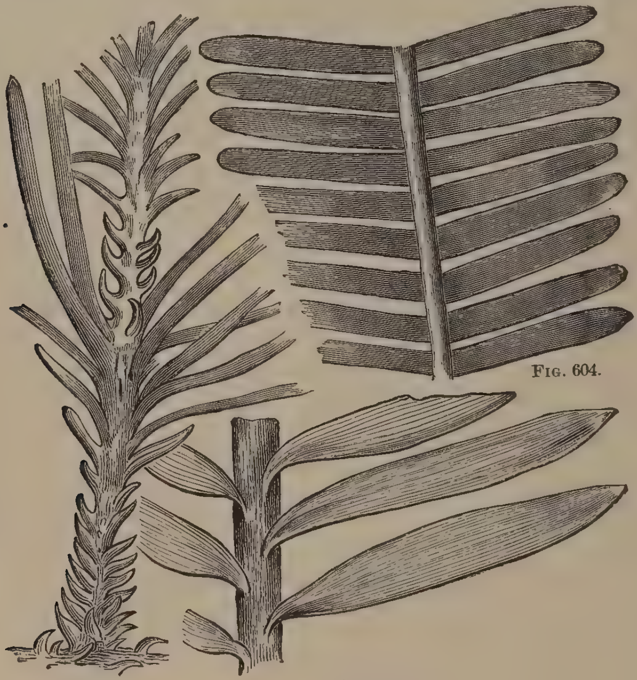

FIG. 604.

FIG. 603.

FIG. 605.

FIGS. 603–605.—TRIASSIC CONIFERS AND CYCADS (after Nicholson): 603. Voltzia heterophylla, a conifer. 604. Pterophyllum Jægeri, a cycad. 605. Podozamites Emmonsi, a cycad.

Plants.

The *flora* of the Trias is very imperfectly known. We find, however, no longer the great coal-making trees of the Carboniferous—Sigillarids, Lepidodendrids, and Calamariæ—though tree-ferns still continue in abundance, but of different types from those of the coal. The forest-trees seem to have been principally *Tree-ferns*, *Cycads*, and *Conifers*, although the last two did not reach their highest development until the next period. For this reason we will put off the fuller discussion of them until we come to that period.

Animals.

Among the Echinoderms we find no longer any Cystids and Blastoids; but *Crinids*, beautiful *lily Encrinites*, with long plumose arms, are very abundant (Fig. 606).

Among *Brachiopods* the familiar square-shouldered forms, including the *Spirifer* family, the *Strophomena* family, and the *Productus* family, are almost if not wholly gone; only a few Spirifers remain. Among *Cephalopods*, we find no longer *Orthoceratites* * or *Goniatites*, but *Ceratites* (Fig. 614) take their place, and *Ammonites* begin. In Ceratites, the suture is more complex than in Goniatites, but not so complex as the subsequent Ammonites. Among *Crustaceans*, we find no longer *Trilobites* nor huge *Eurypterids;* but *Macrourans*, which began in the Carboniferous, are now more abundant, and of more modern forms (Fig. 615).

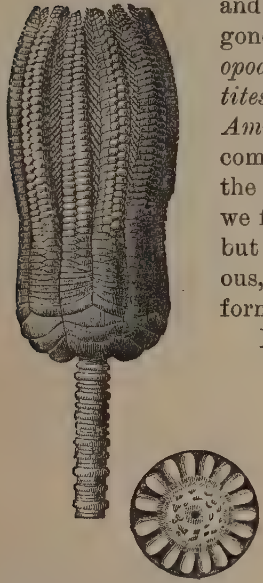

FIG. 606.—Encrinus liliformis.

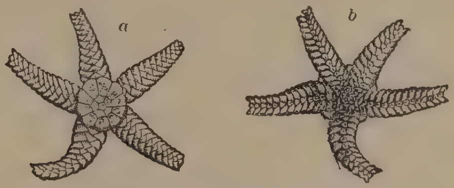

FIG. 607.—Aspidura loricata, an asteroid: *a*, Dorsal; *b*, Ventral surface.

Insects.—As already seen, all the hexapod insects of Palæozoic belong to one family—the Palæodictyoptera—but this was a generalized type connecting the three lower existing orders, viz., Orthopters, Neuropters, and Hemipters. Now, with the opening of the Trias, we have these three orders distinctly differentiated, and Coleopters (beetles) added (Fig. 616). But still the sucking insects are wanting.

Fishes.—Among fishes, still we find *no Teleosts*, only Ganoids and Elasmosbranchs; but while the Ganoids are some of them heterocercal or vertebrated-tailed like the Palæozoic Ganoids, some are only *slightly* vertebrated, and some wholly non-vertebrated-tailed, or homoceral. The *Ceratodus*, a remarkable genus of Dipnoan fishes, one species of which still lives in Australian rivers (Fig. 442, p. 351), is traced back to this period.† Being known in a fossil state only by the curious palatal teeth (Fig. 617), it was formerly classed with Elasmobranchs. The Elasmobranchs are partly *Cestracionts* (Fig. 618) and partly *Hybodonts* (Fig. 619).

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* A very few seem to have crossed the line.

† The recent form is probably a different though closely allied genus, called by Gill *Neo-ceratodus*. (Science, vol. i, p. 725, 1895.)

Amphibians.—Labyrinthodonts have already been described, in connection with the Carboniferous when they first occur. They culminate, however, in size and in complexity of tooth-structure—if not in number and variety—in the Triassic, and then become extinct. In some cases they reached gigantic proportions. The head of the Mastodonsaurus (Fig. 620) was three feet long and two feet wide. The tooth of the typical genus Labyrinthodon was three and a half inches long and one and a half in diameter at the base (Fig. 622). The com-

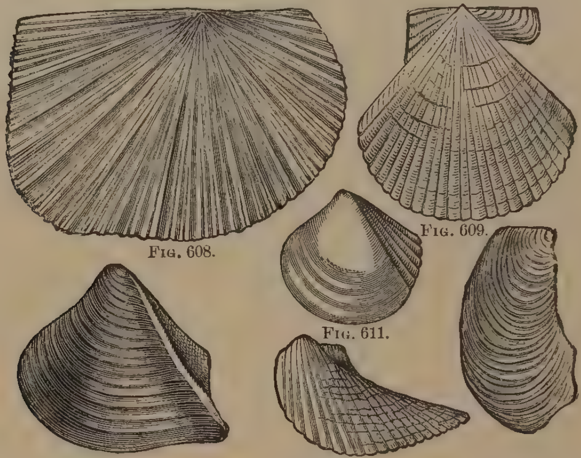
Fig. 608. Fig. 609. Fig. 610. Fig. 611. Fig. 612. Fig. 613.

Figs. 608–613.—Lamellibranchs (after Nicholson): 608. Daonella Lommelli. 609. Pecten Valoniensis. 610. Myophoria lineata. 611. Cardium Rhæticum. 612. Avicula contorta. 613. Avicula socialis.

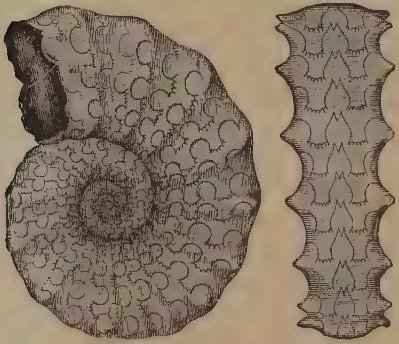
Fig. 614.—Ceratites nodosus.

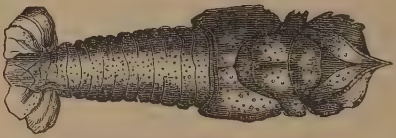
Fig. 615.—Pemphyx Sueurii.

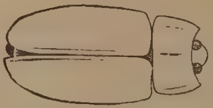
Fig. 616.—Glaphroptera pterophylli (after Heer).

plex labyrinthine structure is shown in Fig. 623. Attention was first drawn to these animals by the discovery in Triassic strata of certain tracks made by a clumsy-footed animal (Fig. 624), which was at first mistaken for a mammal and called Cheirotherium (hand-beast). Its true nature was made known by Prof. Owen, who called it Labyrinthodon.

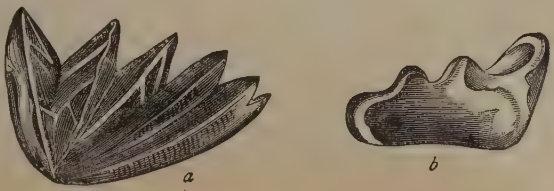

FIG. 617.

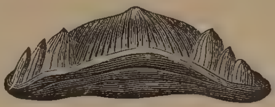

FIG. 618.

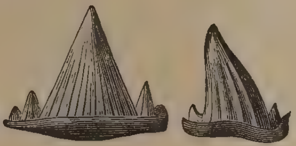

FIG. 619.

FIGS. 617–619.—TRASSIC FISHES: 617. *a*, Dental Plate of Ceratodus serratus; *b*. Dental Plate of Ceratodus altus, Keuper (after Agassiz). 618. Acrodus minimus. 619. Hybodus apicalis (after Agassiz).

Reptiles.—The reptiles of the Triassic are imperfectly known. They belong mainly to three orders: 1. *Rhyncosaurs* (beaked Saurians); 2. *Anomodonts* (lawless-toothed); 3. *Theriodonts* (beast-toothed). The last two are sometimes united into one order,

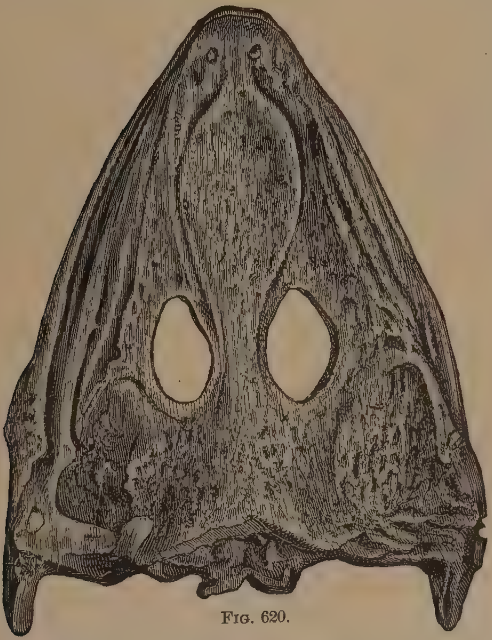

FIG. 620.

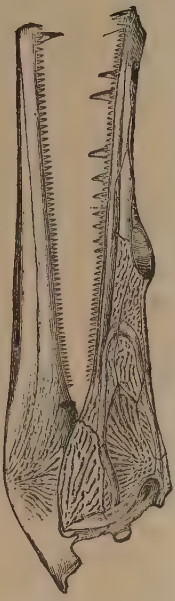

FIG. 621.

FIGS. 620, 621.—TRIASSIC AMPHIBIANS—*Labyrinthodonts:* 620. Mastodonsaurus Jægeri. 621. Trematosaurus (after Huxley).

called *Theromorpha* (beast-form). All these orders are very characteristic of the Trias, although a few Theromorphs are found in the Permian.

The *Rhyncosaurs* had strongly-hooked, horny beaks, like that of a parrot (Fig. 628). The curious reptile Sphenodon, or Hatteria, of New Zealand (Fig. 629), is the nearest living ally.

The *Anomodonts* (lawless-toothed) had jaws covered with horn, like tortoises and birds, sometimes toothless, as in Oudenodon (Fig. 626), and sometimes with two great canines only, as in Dicynodon (Fig. 625). These reptiles were of great size. The head of the Dicynodon tigriceps was twenty inches long and eighteen inches wide.

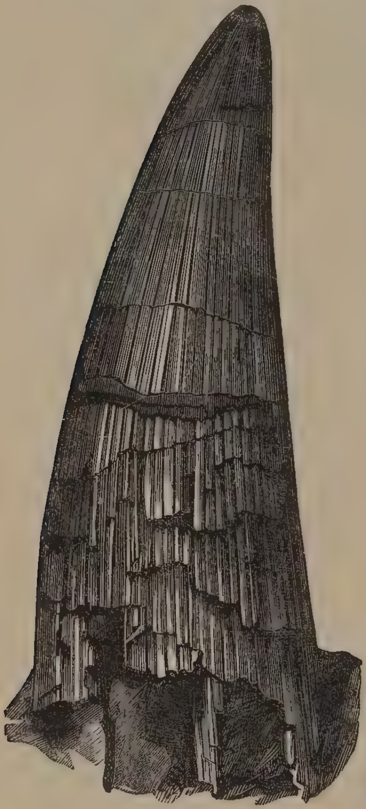

Fig. 622.

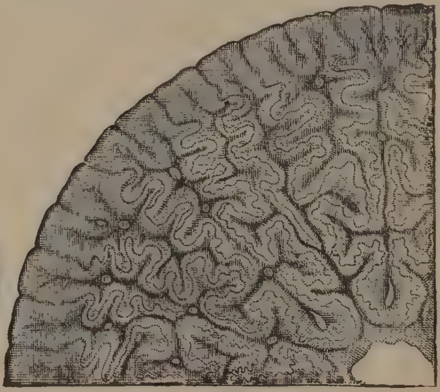

Fig. 623.

Figs. 622, 623.—Triassic Amphibians—*Labyrinthodonts:* 622. Tooth of Labyrinthodon, natural size. 623. Section of same enlarged, showing structure.

The *Theriodonts* (beast-toothed) are so called on account of the resemblance of their teeth to those of the lowest and earliest mammals. The following are the main points of resemblance: 1. The teeth are in three sets, viz., incisors, canines, and molars. 2. The canines are much larger than the others, and separated from them by a wide space (diastema). 3. The molars (jaw-teeth) are in many cases not conical, like reptilian teeth, but have commenced to develop cusps (Fig. 630) like those of mammals, especially of the earliest Mesozoic mammals. (Compare this figure with Fig. 715, p. 466.) The canines of some of these Theriodonts have been found five and six inches long. A large

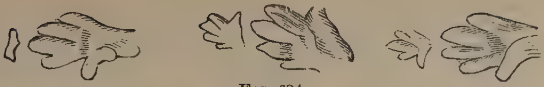

FIG. 624.

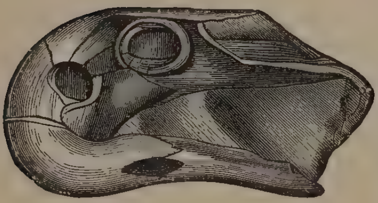

FIG. 626.

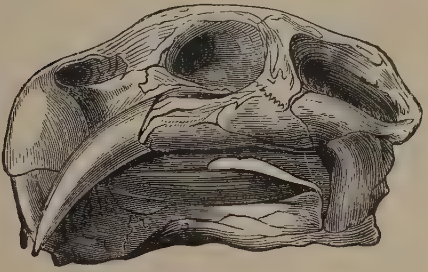

FIG. 625.

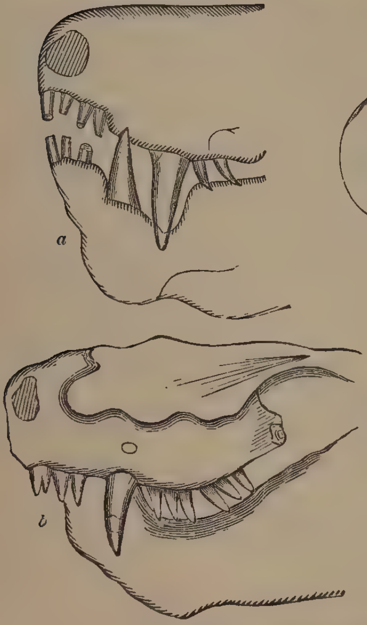

FIG. 627.

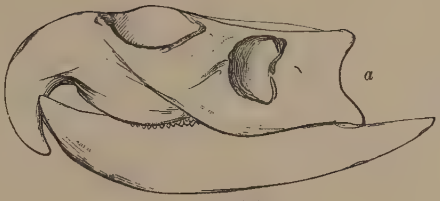

FIG. 628.

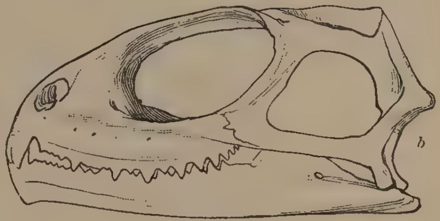

FIG. 629.

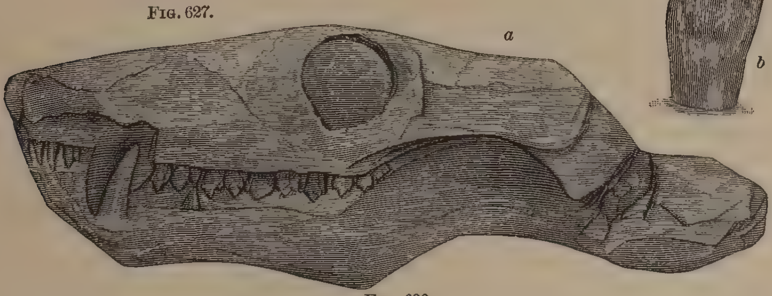

FIG. 630.

FIGS. 624–630.—TRIASSIC REPTILES (after Owen): 624. Tracts of a Cheirotherium—a Labyrinthodont. 625. Dicynodon lacerticeps. 626. Oudenodon Bainii. 627. *a b*, Lycosaurus. 628. Rhyncosaurs—Hyperodapedon, Trias (after Huxley); 629. Sphenodon, living (after Huxley). 630. Galesaurus planiceps—*a*, head; *b*, molar tooth magnified (after Owen).

number of these animals—as also of the previous order—have been found in the Karoo beds of South Africa, and described by Prof. Owen.

Birds.—No birds have yet been found in the strata of the Triassic age, unless we except the so-called *bird-tracks* of the sandstone of the Connecticut Valley and elsewhere, which we will discuss further on.

Mammals.—Remains of two or three *small insectivorous Marsupials*, or perhaps monotremes, have been found in the uppermost Triassic, both of Europe and of the United States. Figures of a tooth of one of these, *Microlestes antiquus*, are given (Fig. 631). The remains of the mammals of the Triassic are so few and fragmentary that it is difficult to make out their affinities, but it is probable that they were a generalized type connecting marsupials with the still lower monotremes and both with Theriodont Reptiles. But as these are found in very small numbers and only in the uppermost Triassic beds, and as similar animals are found in much greater numbers in the Jurassic, it seems best to regard these as anticipations, and to put off the further discussion of the affinities of the earliest mammals until we take up that period.

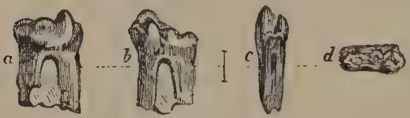

Fig. 631.—Tooth of the Microlestes antiquus.

Mammals probably preceded Birds. This is not a little remarkable. But it must be remembered that Birds are very closely allied to Reptiles, and may be regarded as a secondary offshoot of the reptilian branch.

The sudden coming in of new types here and especially of the characteristic Reptiles is certainly remarkable. They probably originated in the southern hemisphere (Gondwana Land) and migrated thence northward.

Origin of Rock-Salt.

Neither rock-salt nor *coal* is confined to the rocks of any particular age. Both have been formed in every age; both are forming *now*. But as the subject of the origin of coal-deposits was discussed in connection with that age during which it was accumulated in the greatest abundance—the Carboniferous—so the origin of rock-salt is best discussed in connection with the so-called Saliferous or Triassic.

Age of Rock-Salt.—As already stated, rock-salt is found in strata of all ages, and is forming now. Moreover, there is no period which deserves the name Saliferous to the same extent that the Carboniferous deserves its name. The salt of Syracuse, New York, is found in the Upper Silurian; that of Canada, which exists in immense beds 100 feet thick, is found in the Upper Silurian or Lower Devonian; that of

Pennsylvania is Upper Devonian; of Southwest Virginia is sub-Carboniferous; that recently discovered in Kansas is in the Trias;[*] that of Petite Anse, Louisiana, is uppermost Cretaceous or lowest Tertiary (Hilgard). In Europe, the English salt-beds are Triassic, the German beds Permian, Triassic and Jurassic; the celebrated Polish beds at Cracow are Tertiary.

Mode of Occurrence.—Salt occurs in immense *beds* of pure rock-salt, or else impregnating strata. It is obtained by direct mining, or else by boiling down the saline waters either of natural springs or of artesian wells sunk into the salt-bearing strata. The further explanation of its mode of occurrence is best and most concisely given by comparing it with *coal.*

1. Like coal, it occurs in isolated *basins*, but these are far more limited than the great coal-fields. 2. Like coal, it is interstratified with sands and clays, the whole series repeated often many times. In Galicia, for example, there are found seven salt-beds in the same section. In the Kansas Trias there are seven beds. Like coal, also, each bed is usually underlaid with clay. 3. But it differs from coal in the great *thickness* of the beds. In Canada the salt-bed is 100 feet thick (Gibson).[†] In Cheshire, England, there are two beds, one 100 feet, the other 90 feet thick, separated by 30 feet of shale. At Stassfurt, alternating beds of salt and gypsum have been penetrated 1,000 feet, and the bottom not yet reached.[‡] The Berlin salt-well is 4,172 feet deep, and, except the upper 292 feet, penetrates solid salt.[#] 4. Recollecting the somewhat limited extent of basins, it is evident that salt-beds *thin out* far more rapidly than coal. The English salt-beds thin out fifteen feet per mile. Coal, therefore, lies in *extensive sheets*, salt in *lenticular masses.* 5. Coal has its characteristic valuable accompaniment in *iron-beds*, salt in beds of *gypsum.* Thus, as coal-measures consist of repetitions of sands, clays, occasional limestones, with valuable beds of coal and iron-ore many times repeated, so salt-measures consist of sands, clays, and occasional limestones, with valuable beds of salt and gypsum many times repeated. Gypsum-beds are often entirely separate from salt-beds, but each salt-bed is apt to be underlaid by gypsum. 6. While coal-measures are remarkable for the abundance of organic remains, both vegetable and animal, salt-measures are equally remarkable for extreme poverty in this respect. The presence of these remains in the one case, and their absence in the other, are the cause of the difference in the *color of the sandstones.* Coal-measure sandstones are *white* or *gray*, being leached of their oxide of iron by organic matter. Salt-

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[*] Hay, American Geologist, vol. v, p. 65, 1890.

[†] American Journal of Science, vol. v, p. 362, 1873.

[‡] Bischof, Chemical Geology, vol. i, p. 383.

[#] Nature, vol. xv, p. 240, 1877.

measure sandstones are usually *red*, the iron being diffused as coloring-matter.

Theory of Accumulation.—We have already seen (p. 80) that salt-lakes are evaporated residues of river-water or sea-water in dry climates, and are now, most of them, depositing salt; also, that sea-water evaporated deposits first gypsum, then salt: also, that these deposits of salts and gypsum alternate annually with sediments of sand and clay—the salt or gypsum deposit representing the dry season, and the mechanical deposits representing the season of floods. It is, therefore, natural to look in this direction for an explanation of salt and gypsum deposits—to think that salt-basins are dried-up salt-lakes. But the immense thickness of the beds plainly shows that there must have been important modifications of this process. It is plain that the alternations of salt and sedimentary deposit were not *annual* but *secular*.

The conditions under which salt-measures were formed are not certainly known, but most probably they are a dry climate, a low coast, with bordering salt lagoons or bays, partly cut off from the sea by bars, subject to intense evaporation, and resupplied with salt-water by tides or by winds, or perhaps at longer intervals by crust-movements. It is easy to imagine how salt-measures with their alternation of gypsum, salt, and sediments, may thus have been formed. We have examples of the process now going on, on the east shore of the Caspian Sea, in a bay nearly cut off from the main body, where salt has been depositing for ages,* even though the water of the Caspian is much fresher than that of the ocean. On the other hand, it seems to us that the recent observations of Gilbert and Russell on the deposits of the great dried-up lakes Lahontan and Bonneville of the Basin region (p. 590) throw much light on this subject, and that in the phenomena of these deposits we probably have at least an additional method in which salt-measures may be formed. There is abundant evidence that these lakes have filled and dried up and left beds of salt, *more than once*, and that at each refilling the lake *commenced as a fresh lake.* The process was briefly as follows: The great lake, at first fresh, gradually became saline and finally dried away, leaving a thick bed of salt. This salt-bed was then covered by the washing in of fine, impervious clay, and thus *protected from re-solution when the lake re-formed.* This process was repeated in the case of Lake Lahontan three times—that is, there are now beneath the salt-lakes of this region, two beds of salt separated by clay, and the third deposit is now forming. Salt-beds are now reached and worked in many places of this region by penetrating the fine clay which marks the places of the old lakes.*

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* Ochsenius, Proceedings of the Academy of Natural Sciences, Philadelphia, 1888, p. 181.

In the deposits of salt-lakes or saturated lagoons we would not expect to find many animal remains, but the tracks of animals along their muddy shores, as also sun-cracks and rain-prints, would be found as on other shores. Now, although in the strata associated with salt organic remains are rare, shore-marks of all kinds are common. Thus deposits of gypsum and salt may be taken as *evidence of dry climate.*

SECTION 2.—JURASSIC PERIOD.

This is the culminating period of the Mesozoic era and Reptilian age. In it all the characteristics of this age reach their highest development. We must discuss this somewhat more fully than the last.

The strata belonging to this period are magnificently developed in the Jura Mountains, and hence the name Jurassic. These mountains are an admirable illustration of the manner in which ridges and valleys are formed by the folding of strata (Fig. 632); they also abound in fossils of this period.

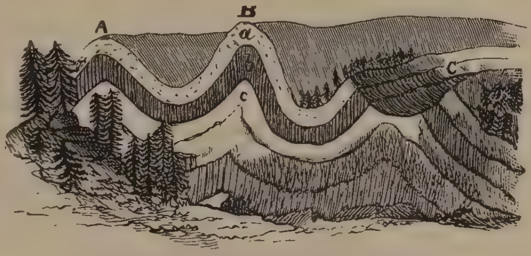

FIG. 632.—Section of the Jura Mountains.

Some English geologists call the period *Oölite* (egg-stone) on account of the abundant occurrence in that country of a peculiar limestone composed often wholly of small, rounded grains like the roe of a fish. They divide the whole period into three epochs, viz.: 1. *Lias;* 2. *Oölite proper;* 3. *Wealden.*† They also subdivide the Oölite proper into *Lower*, *Middle*, and *Upper* Oölite, separated by intervening Oxford and Kimmeridge clays. All these divisions and subdivisions are well shown in the following section passing from London westward. This

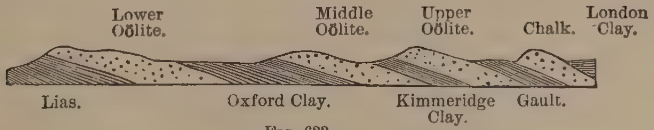

FIG. 633.

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* Gilbert, Lake Bonneville, Wheeler's Survey, vol. iii; American Journal of Science, vol. xxxi, p. 384, 1886; Russell, Lake Lahontan, Monograph of United States Geological Survey, vol. xi, pp. 2, 261, and 268.

† The Wealden is now often put in the Cretaceous.

section is interesting not only as exhibiting all the divisions and subdivisions of the Oölitic period, but also as showing their conformity among themselves and with the overlying chalk, and the unconformity of these with the overlying Tertiary. It also shows how parallel ridges and intervening hollows are formed by the outcroppings of a series of strata alternately hard and soft.

Origin of Oölitic Limestones.—These are composed of rounded grains with concentric structure. We have already seen, page 163, that on coral shores a kind of sand is formed by the action of waves on fragments of coral and shells. These fragments are rounded by attrition; then often enlarged by deposit of concentric layers of lime from the saturated sea-water; and, finally, cemented by the same into hard rock. Recent observations show that certain low forms of Algæ are in many, if not all, cases an important agent in determining the deposits of the lime carbonate by withdrawing the CO_2 necessary for its solution.* In some such way oölitic limestones have been formed in all geological periods. We conclude, therefore, that in Jurassic times great coral reefs existed where England now stands. In the Jura Mountains it is believed that the remains of fossil circular reefs or atolls of this period are still detectable (Heer).

Jurassic Coal-Measures.—In the Jurassic times we have reproduced on a large scale the conditions favorable to luxuriant growth of plants, and for their accumulation and preservation in the form of *coal.* Hence in many countries we have Jurassic coal-fields. To this period belong the Yorkshire coal of England and the Brora coal of Scotland. To this or the previous period belong the coal-fields of North Carolina and Eastern Virginia, and some of the coal-fields of India † and China. The fine coal-measures of New South Wales, Australia, covering an area of 20,000 square miles, are partly, though not mainly, Jurassic or Triassic, as are also those of South Africa. Jurassic coal-measures have a general structure similar to those of the Carboniferous. Like the latter, they consist of alternations of sands and clays, and occasional limestones, containing seams of coal and beds of iron-ore. The iron-ore too is of the same kind, viz., *clay iron-stone.* We find here also under-clays, with stumps and roots, and roof-shales filled with leaf-impressions. It is fair to conclude, therefore, that the mode of accumulation was similar to that already described, viz., in marshes subject to occasional floods. Jurassic coal, though perhaps inferior as a general rule to Carboniferous, is often of good quality, occurring in thick and profitable seams.

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* Rothpletz, American Geologist, vol. x, p. 279, 1892.

† The plant-beds of India (Gondwana series of Indian geologists) are Permian to Jurassic inclusive. (Manual of Indian Geology, p. 102 *et seq.*)

Dirt-Beds—Fossil Forest-Grounds.—Coal-seams with their underlying clays are fossil *swamp-grounds*; dirt-beds are fossil *soils* or *forest-grounds*. The one graduates insensibly into the other, and both are occasionally found in all strata, from the Devonian upward. In the Upper Oölite of England, at the Isle of Portland and elsewhere, there occurs an interesting example of such a fossil forest-ground with the erect stumps and ramifying roots still *in situ*, though silicified, and the logs, also silicified, still lying on the fossil soil (Figs. 634, 635). It is evident that the sequence of events at this place in Jurassic times was as follows: 1. The place was sea-bottom, and received sediment which consolidated into Portland-stone. 2. After being flooded and covered with river-deposit, it was raised to land and became forest-ground, covered with trees and other vegetation peculiar to that time, the decaying leaves of which accumulated as a rich and thick vegetable mold. 3. It became flooded with fresh water, and the trees therefore died and rotted to stumps. 4. The whole ground, with its stumps and logs, became covered with mud, which hardened into slates. 5. Finally, the whole was raised into high land, and in the first figure (Fig. 634) tilted at a considerable angle.

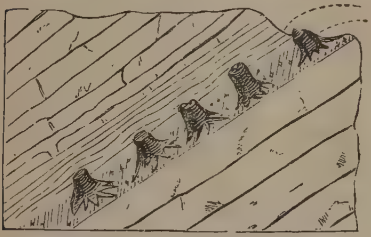


FIG. 634.—Section in Cliff east of Lulworth Cove: *a*, Dirt-bed.

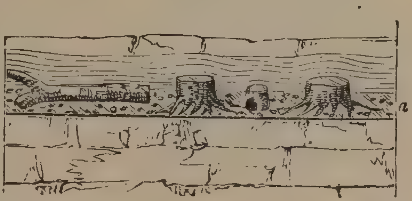


FIG. 635.—Section in the Isle of Portland: *a*, Dirt-bed.

Thus, we have here not only an old forest-ground with its vegetable mold, but also the stumps and logs of the trees which grew there, still in place; and closer examination easily detects the kinds of trees which grew in the forest. They are *Cycads* and *Conifers* (Figs. 636, 637, and 641, 642). Still further, there is good reason to believe that the remains of some of the animals which roamed these forests have also been found. Of these we will speak in their proper place.

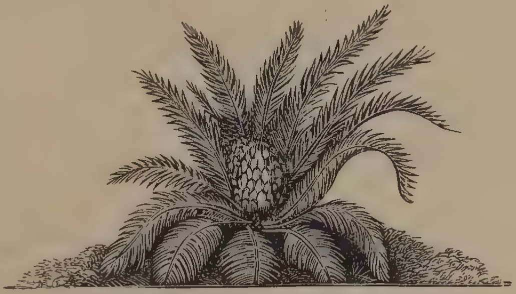


FIG. 636.—Zamia spiralis, a Living Cycad of Australia.

Plants.

Although the conditions under which coal was accumulated were probably similar in all geological periods, yet the kinds of plants out of

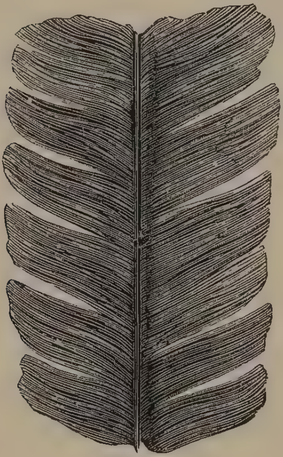


FIG. 637.

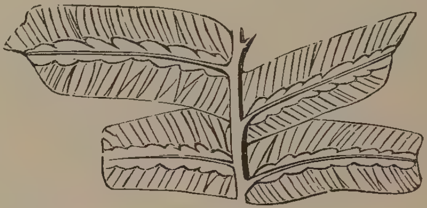


FIG. 638.

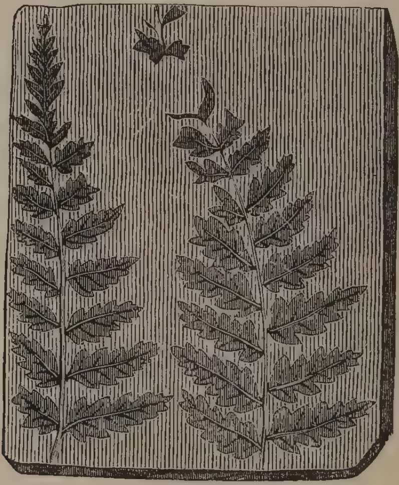


FIG. 639.

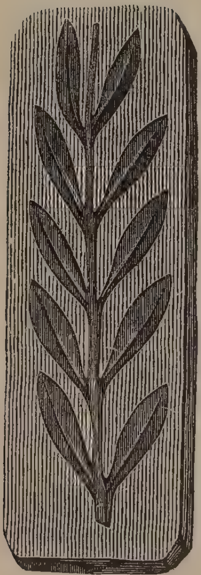


FIG. 640.

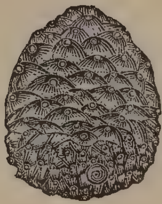


FIG. 641.

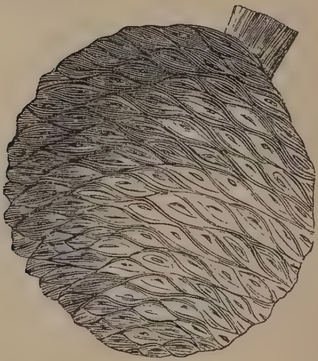


FIG. 642.

FIGS. 637-642.—JURASSIC PLANTS—*Cycads and Ferns:* 637. Pterophyllum comptum (a Cycad). 638. Hemitelites Brownii (a Fern). 639. Coniopteris Murrayana. 640. Pachypteris lanceolata. *Conifers:* 641. Cone of a Pine. 642. Cone of an Araucaria.

which the coal was made varied. As already seen, the principal coal-plants of the Carboniferous period were vascular Cryptogams. On the contrary, the principal coal-plants of the Jurassic period were *Ferns*, *Cycads*, and *Conifers*. The Jurassic may be called the *age of Gymnosperms*, as the Carboniferous was the age of Acrogens. The Gymnosperms, especially the family of Cycads, reached here their highest development. This is shown in diagram on page 294. The leaves (Fig. 637) and short stems of Cycas and Zamia (Fig. 644) are found very abundantly in connection with the coal-bearing strata. It is probable, therefore, that the coal is composed largely of these plants. Some remains of Jurassic plants are given (Figs. 637–642), and also of living Cycads (Figs. 636, 643), for comparison.

Animals.

The animals of the Jurassic, marine, fresh-water, and land, were very abundant, and have been well preserved. It is impossible, therefore, in the lower departments, to do more than touch lightly the most salient points. In the higher departments we will dwell a little longer.

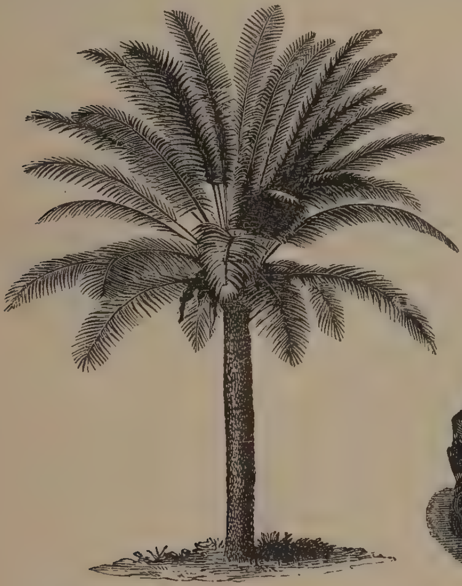


Fig. 643.—Cycas circinalis, × $\frac{1}{120}$, a Living Cycad of the Moluccas (after Decaisne).

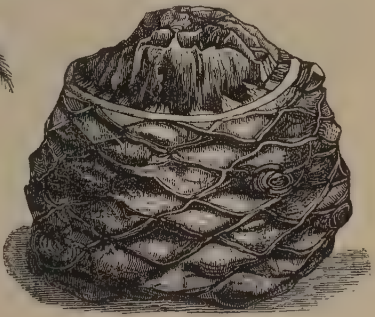


Fig. 644.—Stem of Cycadeoidea megalophylla, × $\frac{1}{8}$.

Corals have assumed now the modern type and style of partitions (Fig. 645). Among **Echinoderms**, the *Crinids*, or plumose-armed Crinoids, are very abundant and very beautiful; in fact, they seem to have reached their highest point in abundance, diversity, and gracefulness of form (Figs. 646, 647). But the free forms, Echinoids and Asteroids, are now equally abundant (Figs. 648–650).

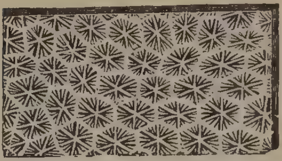


Fig. 645.

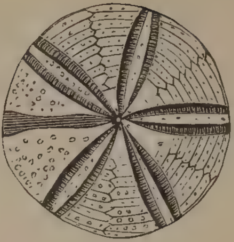


Fig. 649.

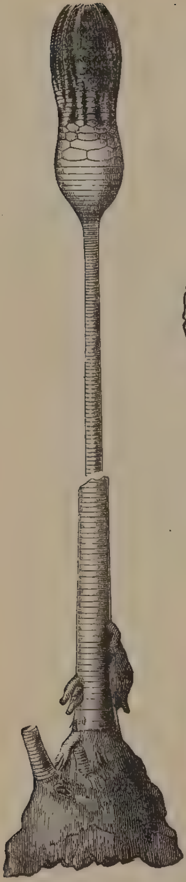


Fig. 646.

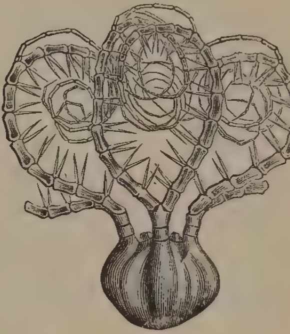


Fig. 647.

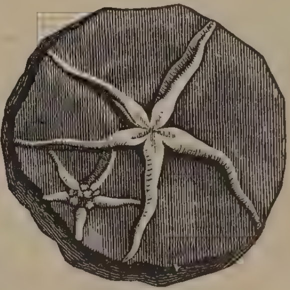


Fig. 648.

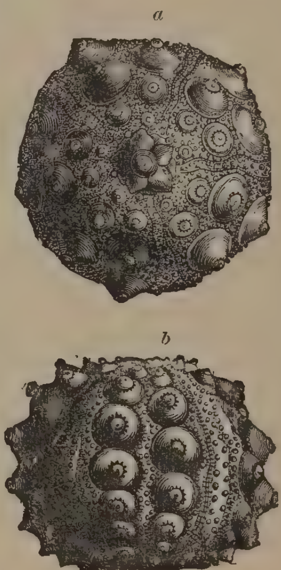


Fig. 650.

Figs. 645–650.—Jurassic Corals and Echinoderms: 645. Prionastrea oblongata. 646. Apiocrinus Roissianus. 647. Saccocoma pectinata (a free Crinoid). 648. Asteria lombricalis. 649. Clypeus Plotii. 650. *a b*, Hemicidaris crenularis.

Brachiopods are still abundant, though far less so than formerly; but they now belong almost wholly to the modern or sloping-shouldered

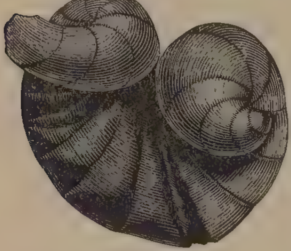


Fig. 651.

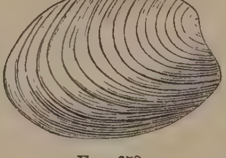


Fig. 652.

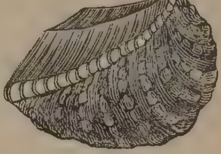


Fig. 653.

Figs. 651–653.—Jurassic Lamellibranchs and Brachiopods of England: 651. Diceras Arietina, Middle Oölite (after Nicholson). 652. Astarte excavata. 653. Trigonia clavellata.

types, such as Terebratula and Rhynchonella. Only a very few small specimens of the Palæozoic type linger until the Lias.

Lamellibranchs, or common bivalves, are extremely abundant. Among the common and characteristic forms are Trigonia, Gryphæa, and Exogyra, belonging to the oyster family; and the strangely-shaped Diceras (Fig. 651). It is interesting, also, to observe here the first appearance of the genus *Ostrea* (oyster).

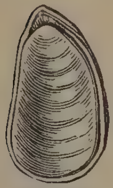


Fig. 654.

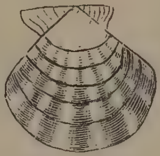


Fig. 655.

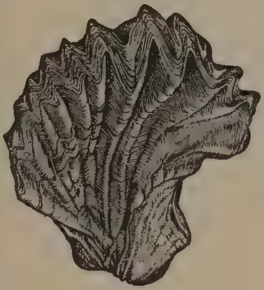


Fig. 656.

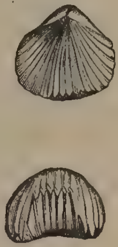
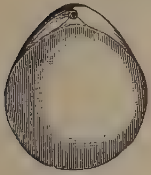


Fig. 657.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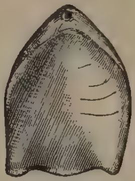


Fig. 659.

Figs. 654–659.—Jurassic Lamellibranchs and Brachiopods of England: 654. Ostrea Sowerbyi. 655. Pecten fibrosus. 656. Ostrea Marshii. 657. Rhynchonella varians. 658. Terebratula sphæroidalis. 659. Terebratula digona (after Nicholson).

Cephalopods.—One of the most striking characteristics of the Jurassic period is the culmination of the class of Cephalopods in *number*, *diversity* of forms, and, if we except some of the Silurian Orthoceratites, in *size*. They were represented by the Ammonites and the Belemnites, the one belonging to the order of Tetrabranchs, or shelled, the other to the Dibranchs, or naked Cephalopods. It is important to observe that the highest order of Cephalopods, the Dibranchs, by far the most abundantly represented at the present time, were introduced *here* for the first time.

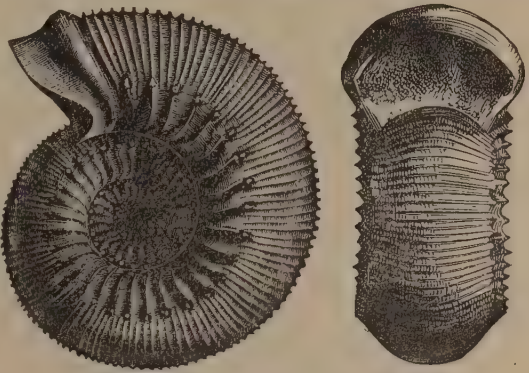
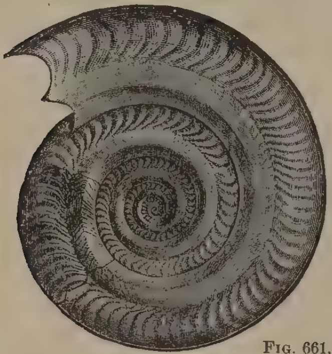


Fig. 660.—Ammonites Humphreysianus.

Ammonites.—The Ammonite family, which is distinguished, as already explained (p. 329), by the outer or ventral position of the siphuncle and the complexity of the suture, is represented in extreme



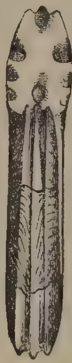


FIG. 661.

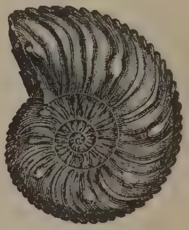


FIG. 662.

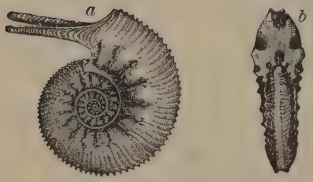


FIG. 663.

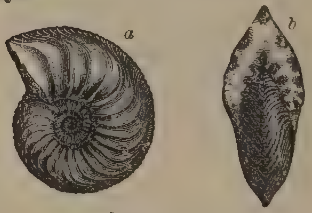


FIG. 664.

FIGS. 661–664.—JURASSIC CEPHALOPODS—*Ammonites;* 661. Ammonites bifrons. 662. Ammonites margaritanus. 663. Ammonites Jason: *a*, side view; *b*, showing suture. 664. Ammonites cordatus: *a*, side view; *b*. showing suture.

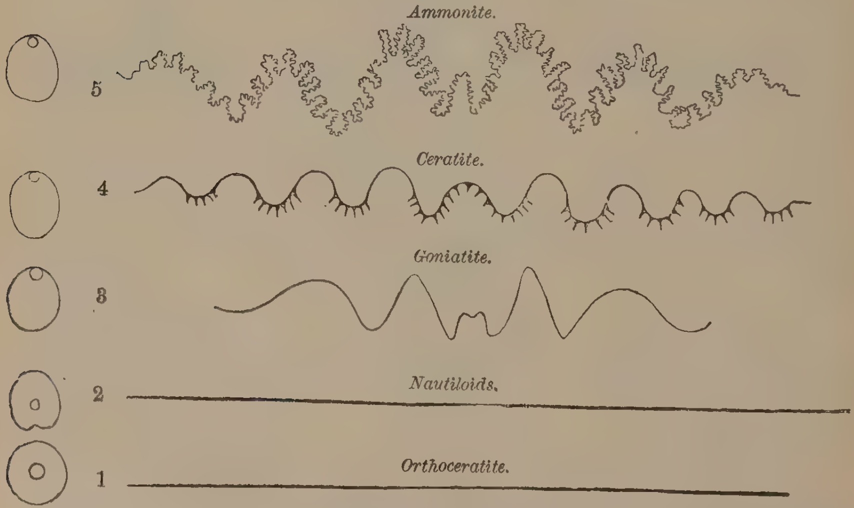


FIG. 665.—Diagram showing Form of the Suture, Position of Siphuncle, and Order of First Appearance of Families in Cephalopods.

abundance by the type-genus *Ammonites.** Nearly 2,000 species of this genus are known, ranging in time from the Triassic through the Cretaceous. They are therefore characteristic of the Mesozoic. They varied extremely in shape, and in size from half an inch to a yard or more in diameter. The accompanying figures represent some of the most common species.

In the genus Ammonites the distinguishing character of the family, viz., the complexity of the suture, reached its highest point. In this genus, the edge of the septa, which was only zigzag in Goniatite, and lobed in the Ceratite, becomes elaborately *frilled.* We give in Fig. 665 the form of suture in the type-genera of the different orders of shelled Cephalopods, in the order of their first appearance. In each case the suture is supposed to be divided on the inner or dorsal surface, and spread out, so that the central part in the figure represents the outer or ventral portion, and the two extremities the dorsal. The evolution of form and structure was in the following order: First the straight *Orthoceras*, then

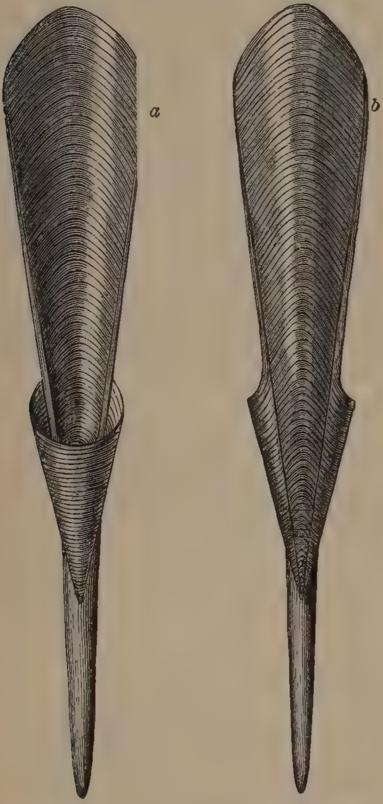


Fig. 666.

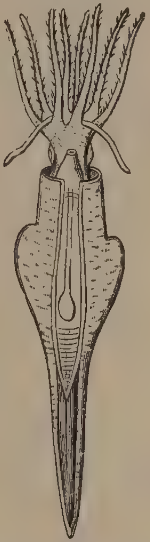


Fig. 667.

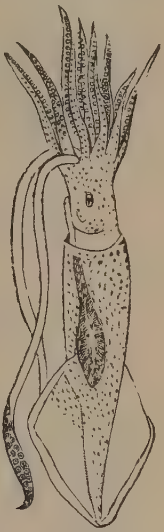


Fig. 668.

Figs. 666–668.—666. Internal Shell of Belemnite (restored by D'Orbigny). 667. The Animal (restored by Owen). 668. A living Sepia for comparison.

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* This genus is now broken up into many, but it is still convenient to retain the name for a very distinct group of Cephalopods.

the curved *Gyroceras*, then the coiled *Nautiloids*, then the simple suture became angled in *Goniatite*, then scalloped in *Ceratite*, and finally complexly frilled in *Ammonite.* It is remarkable, however, that one of the simpler forms, viz., the nautiloids, although also one of the earliest, has outlived them all. The corresponding figures on the left are sections showing the position of the siphuncle.

The order in which the several genera appeared, and their continuance, are shown in the diagram (Fig. 675) on page 451.

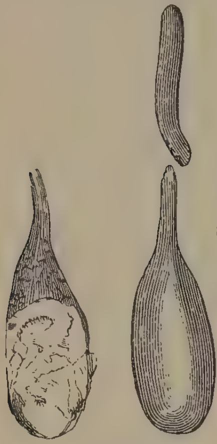

Fig. 669.

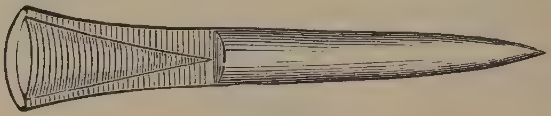

Fig. 670.

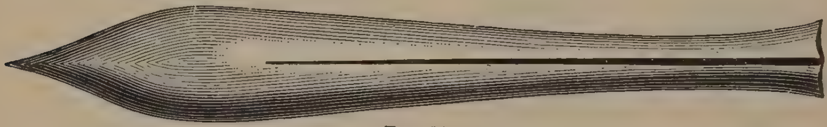

Fig. 671.

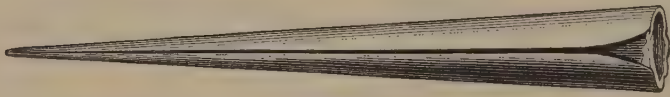

Fig. 672.

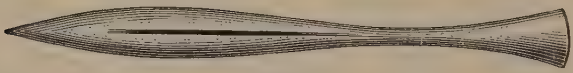

Fig. 673.

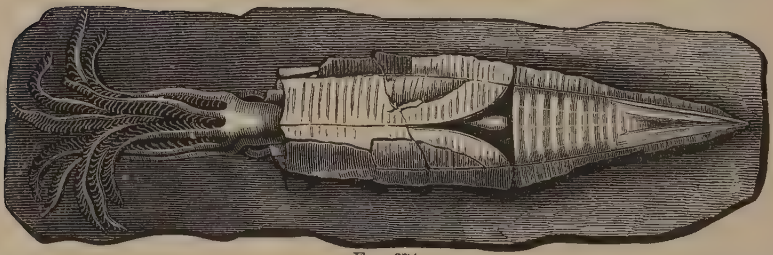

Fig. 674.

Figs. 669–674.—669. Fossil Ink-Bags of Belemnites. 670. Belemnites Owenii. 671. Belemnites hastatus. 672. Belemnites unicanaliculatus. 673. Belemnites clavatus. 674. Acanthoteuthis antiquus (after Mantell).

Belemnites.—The Belemnite (*βέλεμνον, a dart*) was nearly allied to the squid and cuttle-fish of the present day. Like the squid, it had an internal bone (the pen of the squid), except that the bone is much larger and heavier in the Belemnite. It is this bone, or the lower portion of it, which is usually fossilized (Figs. 670–673). When perfect it is expanded and hollow at the upper end, and in the hollow is a small, conical, chambered, siphuncled shell, the *phragmocone.* Fig. 666, *a* and *b*, shows the perfect bone, and Fig. 670 the upper part broken and the phragmocone in place. Like the squid, too, it had an ink-bag, from which it doubtless squirted the inky fluid to darken the water and escape its enemy. These ink-bags are often well preserved (Fig. 669), and the fossil ink has been found to make good pigment (sepia), and drawings of these extinct animals have actually been made with the fossil ink of their own ink-bags (Buckland). Belemnites were some of them of great size, and evidently formidable animals. The bone of the *Belemnites giganteus* has been found two feet long and three to four inches in diameter at the larger or hollow end. A very perfect specimen of an allied genus, from the Oölite of England, is shown in Fig. 674.

The following diagram shows the order of succession of families of the class Cephalopoda:

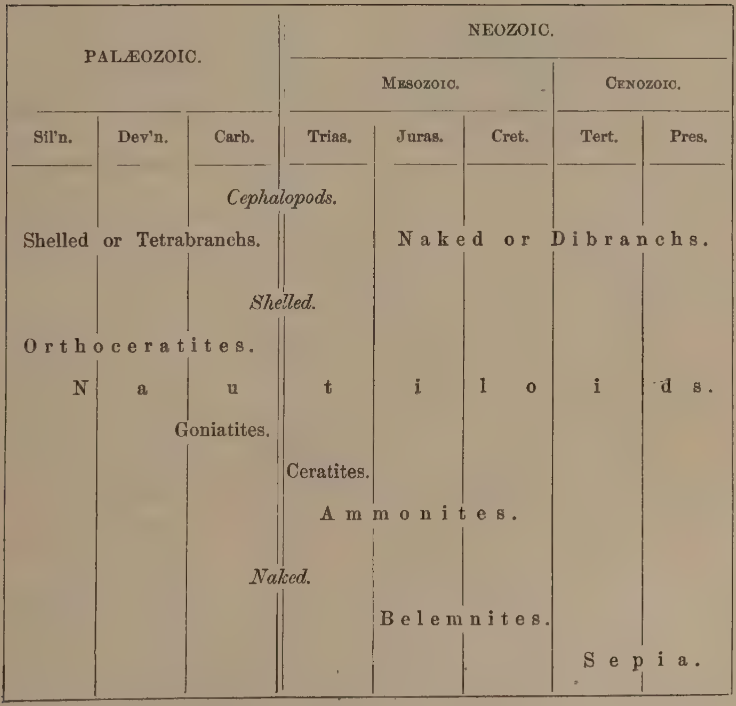

Fig. 675.—Diagram showing Distribution of Cephalopods in Time.

We have shown how the different *shelled* forms were derived. Now *the phragmocone corresponds to the shell.* We may suppose then that in *naked* forms the shell first became small and then was overgrown and inclosed by the soft parts.

Crustacea. — Crustacea were represented in the Palæozoic first by the Trilobites; then Eurypterids; then Limuloids; then, in the last period, by a few Macrourans. In the Triassic the Macrourans became more abundant and of more modern type. In the Jurassic the Macrourans continue, with also many Limuloids, but the former make here a decided approach to the Brachyourans or true crabs, by the shortening of the tail in some (Fig. 676); and the earliest true crab, Palæinachus—a spider-crab—has been found in the Jurassic of England. The same change—i. e., shortening of the tail—may be seen in the embryonic development of a crab (Fig. 678).

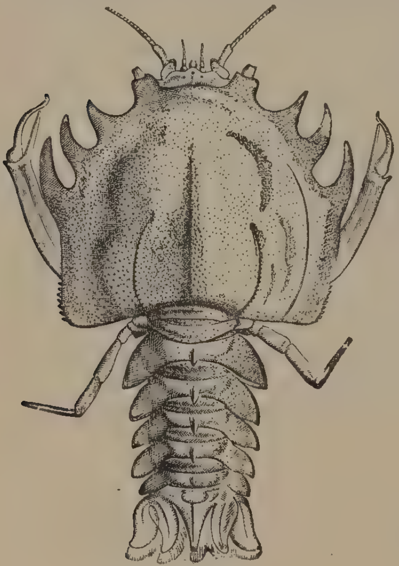
FIG. 676.

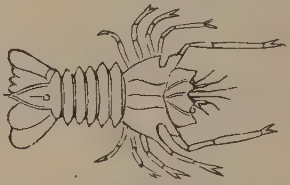
FIG. 677.

FIGS. 676, 677.—JURASSIC CRUSTACEANS: 676. Eryon arctiformis, Solenhofen. 677. Eryon Barrovensis, England.

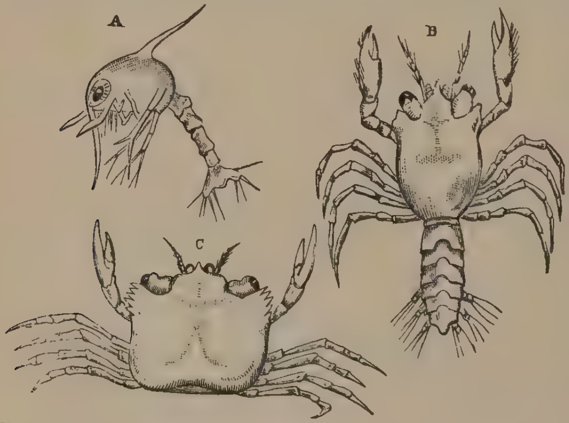

FIG. 678.—Development of Carcinus mœnas: A, zoœa stage; B, megalops stage; C, final state (after Couch).

Insects. — As might be expected from the abundant forest vegetation, insects have been found in considerable numbers and variety (Figs. 679–684). According to Heer, 143 species of insects are known from the Lias alone. Of these, about three fourths are beetles.

The earliest of the higher group of insects seem to have been introduced here, although they do not become abundant until the Tertiary.

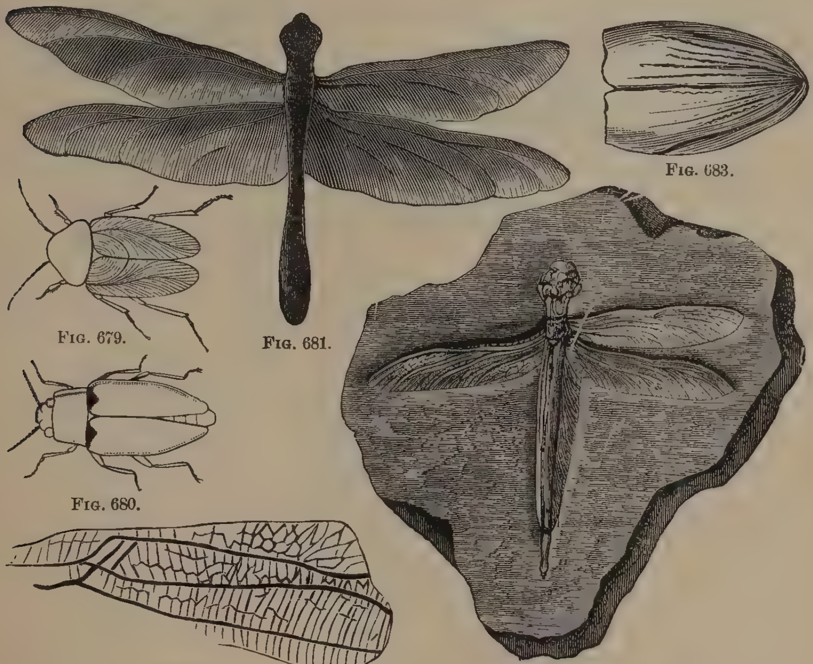

Fig. 683.

Fig. 679.

Fig. 681.

Fig. 680.

Fig. 684.

Fig. 682.

Figs. 679–684.—Jurassic Insects: 679. Blattina formosa (after Heer). 680. Glaphyroptera gracilis (after Heer). 681. Æschna eximia (Hager). 682. Libellula. 683. Buprestidium. 684. Hemerobioides giganteus.

Fishes.—It will be remembered that the Elasmobranchs of the Palæozoic were nearly all Cestracionts, or crushing-toothed sharks. The Hybodonts, or sharks with teeth pointed, but rounded on the edges, commenced in the Carboniferous and increased in the Triassic. Now, in the Jurassic the Cestracionts continue (Fig. 685), but in diminished numbers. The Hybodonts culminate (Fig. 686), and the *Squalodonts*, or modern sharks, with lancet-shaped teeth, commence in small numbers. Rays (Fig. 687), which may be regarded as among the most specialized of Elasmobranchs, are found in considerable numbers in the Jurassic.

Ganoids continue, but take on far more modern forms, and have now in most cases lost the vertrebrated structure of the tail-fin, thus foreshadowing the Teleosts, which appear in the next period. Among the most characteristic Ganoids of this period, and, in fact, of this age, are the Pycnodonts, a family characterized by a broad, flat body, rhomboidal enameled scales, pavement palatal teeth, and persistent notochord (Fig. 688).

Reptiles.—The huge reptiles which form the distinguishing feature of this age culminate in the Jurassic period. Their number and variety are so great that we can only select a few from each order for description. They were emphatically rulers in every department of Nature—rulers of the sea, of the land, and of the air. We shall treat of them under the three heads thus indicated, viz.: 1. *Enaliosaurs* (sea-saurians), or rulers of the sea; 2. *Dinosaurs* (huge saurians), or rulers of the land; and, 3. *Pterosaurs* (winged saurians), or rulers of the air. The first were wholly swimming, the second walking, the third flying, saurians. Intermediate between the first and second was a fourth order, the *Crocodilians*, which both swam and crawled.

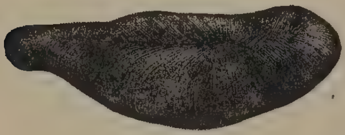

FIG. 685.

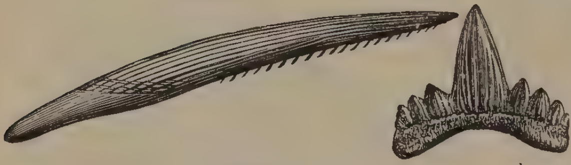

FIG. 686.

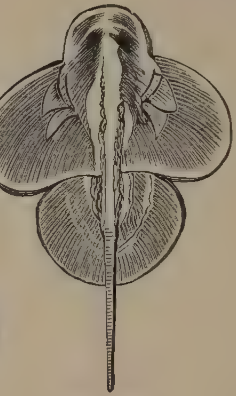

FIG. 687.

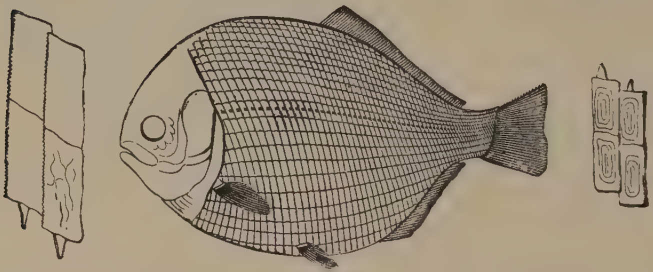

FIG. 688.

FIGS. 685–688.—JURASSIC FISHES—*Elasmobranchs:* 685. Tooth of Acrodus nobilis. 686. Hybodus reticulatus, Spine and Tooth. 687. Squatina acanthoderma. 688. *Ganoid:* Tetragonolepis, restored, and Scales of the same.

1. *Enaliosaurs.*—From the immense variety of these we select only two for description as representative genera, viz., *Ichthyosaurus* and *Plesiosaurus* (Figs. 689 and 690).

The *Ichthyosaurus* (*fish-lizard*) was a huge animal, in some cases thirty to forty feet in length, with a stout body, short neck, and enormous head, sometimes five feet long, and jaws set with large conical, striated teeth, sometimes 200 in number. The enormous eyes, sometimes fifteen inches in diameter, were provided with radiating, bony

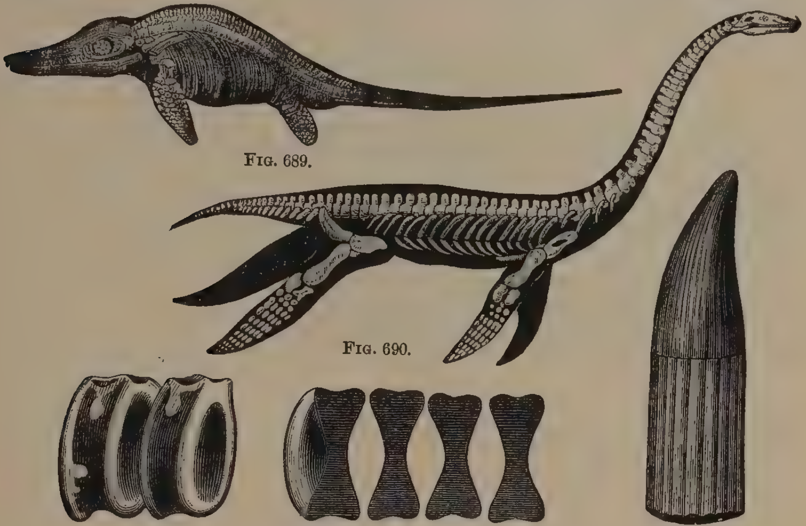

FIG. 689.

FIG. 690.

FIG. 691.

FIG. 692.

FIGS. 689–692.—JURASSIC REPTILES—*Ichthyosaurus and Plesiosaurus;* 689. Ichthyosaurus communis, × $\frac{1}{100}$. 690. Plesiosaurus dolichodeirus, restored, × $\frac{1}{80}$. 691. Vertebræ of Ichthyosaurus and Section of same, showing structure. 692. Tooth of Ichthyosaurus, natural size.

plates (sclerotic bones), as are the eyes of birds and some living and many extinct reptiles, apparently for adjusting the eye to different distances. The tail was long, and provided terminally with a

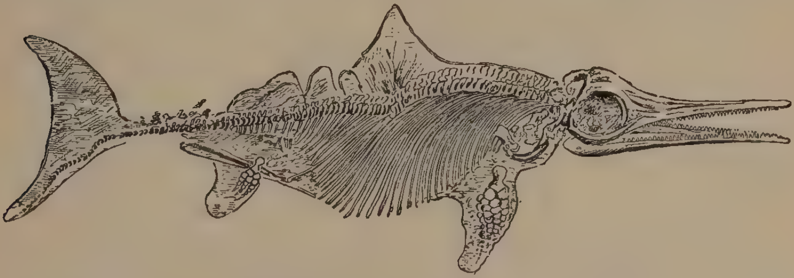

FIG. 693.—Ichthyosaurus quadriscissus, found in Würtemberg, showing Tail-Fin and Dorsal Fin, × $\frac{1}{12}$ (after Fraas).

vertical, fin-like expansion, unsupported by rays (Owen). This prevision of Owen has been entirely verified by recent discoveries in the Lias of Würtemberg of specimens which clearly show this vertical expansion, and also the remarkable fact that the vertebral column runs into the lower instead of the upper lobe, as in sharks. Median dorsal fins are also shown (Fig. 693). In addition to the powerful fin-tipped tail, the locomotive organs were four short stout paddles, composed of numerous closely-united bones, but without distinct toes. These paddles were surrounded by an expanded, ray-supported web (Fig. 694), which greatly increased their surface, and therefore their efficiency as swimming-organs (Lyell). The bodies of the vertebræ were not united by *ball-and-socket* joint, as in most living reptiles, but were *bi-concave* (amphicœlous), like those of fishes (Fig. 691).

That the *habits* of the creature were predatory and voracious is sufficiently attested by the teeth. It is further proved by the contents of the stomach, which are sometimes partly preserved. These consist largely of *fish-scales.*

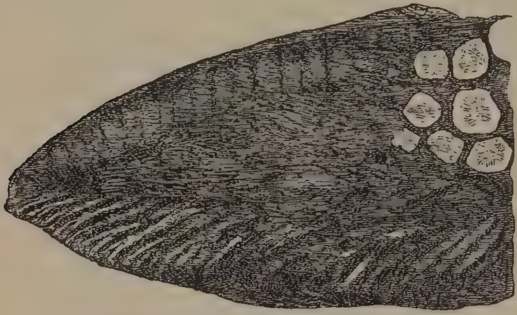

FIG. 694.—Paddle-Web of an Ichthyosaurus.

From the description given above it is plain that the Ichthyosaurus combined in a remarkable degree the characters of saurian reptiles with those of fishes. The vertically-expanded tail-tip, the paddles, with surrounding ray-supported web, and the bi-concave vertebral bodies, are all decided fish characters. In most other respects it was reptilian. This combination is expressed in the name.

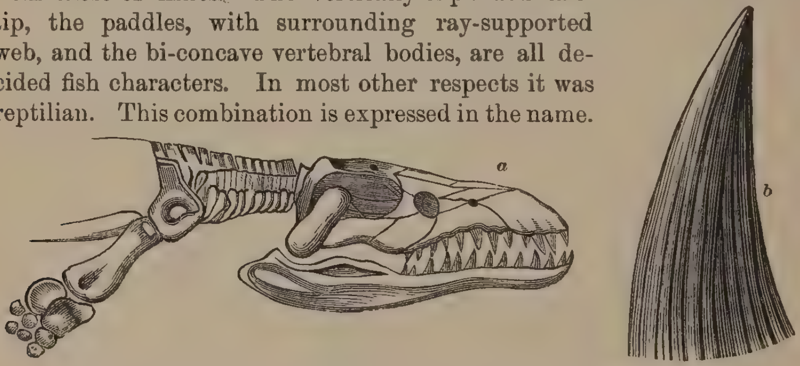

FIG. 695.—*a*, Head of a Pliosaurus, greatly reduced; *b*, Tooth of the same, natural size.

The *Plesiosaurus* (allied to a lizard) was a less heavy and powerful animal than the last. It was remarkable for its short, stout, almost turtle-shaped body; its long, snake-like neck, consisting of twenty to forty vertebræ; its small head; its short tail, unadapted for powerful propulsion; its long and powerful paddles, which were its sole swimming-organs; and its bi-concave vertebral bodies. Recent discoveries in Kansas show that sclerotic bones were present in this order also.* Sixteen species have been found in the Jurassic and Cretaceous rocks of Great Britain alone, and one, *P. dolichodeirus*, was twenty-five to thirty feet long (Fig. 690), with paddles six to seven feet long.

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* Williston, Science, vol. xvi, p. 262, 1890.

The *Pliosaurus* (more lizard-like) (Fig. 695) had the large head and short neck of the Ichthyosaurus, with the powerful paddles of the Plesiosaurus. A perfect paddle of this animal has been found seven feet long (Fig. 696); the animal was probably at least forty feet long.

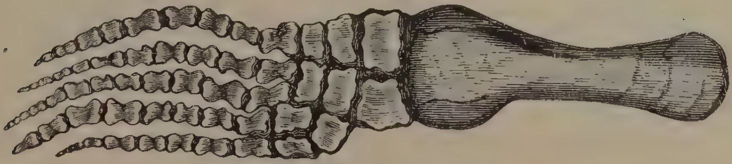

FIG. 696.—Paddle of a Pliosaurus, × $\frac{1}{20}$.

Intermediate between this group and the next—inhabiters both of land and water—*Crocodilians* existed in great numbers, and of great size.

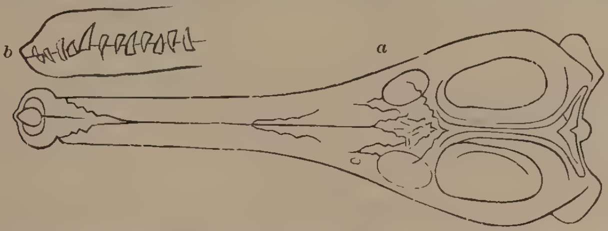

FIG. 697.—Teleosaurus brevidens: *a*, skull; *b*, side view of snout showing the teeth (after Phillips).

Some, like the Teleosaurus (Fig. 697), were narrow-snouted like the Gavials of the Ganges, but had amphicœlous vertebræ like the Enaliosaurs.

2. *Dinosaurs.*—Among these were the largest reptiles—in fact, the largest land-animals that have ever existed. They were also in many respects the highest of all reptiles, since they possessed many characters which connected them closely with mammals, and especially with birds.

Connecting Characters.—The most important of these were: (1) Large limb-bones and firm sacrum composed of several (four to five) consolidated vertebræ. These characters show that these animals *walked* with a free step, the body well borne above the ground, like mammals and birds, and did not crawl in the manner of reptiles. (2) In many cases the hind-legs were very large and long, and the fore-legs very small in comparison. This, together with the backward elongation of the ischium (Fig. 698, B)—suitable for erecting the body—show that some of them walked habitually on their hind-legs alone, in the manner of birds. (3) Like birds and some mammals, many Dinosaurs *tread on their toes* (digitigrade) and not like reptiles on the whole foot (plantigrade). (4) Like birds, also, many—but not all—had only three functional toes, and therefore made tridactyle tracks; and even the number of toe-joints follows the order of those of birds—i. e., there were three in the inner toe, four in the middle, and five in the outer toe. (5) Still more curious is the resemblance to birds, in the structure of the ankle-joint. In mammals the joint is between the shank-bones and the tarsus. In reptiles the motion takes place in the middle of the tarsus. In birds the upper tarsals (astragalus and calcaneum) are consolidated with the shank and the lower tarsals with the metatarsals, and the joint is of course between these two bones. Now some Dinosaurs are like birds in this regard. Fig. 698, A B C, illustrates this point. We shall very briefly describe only the most remarkable.

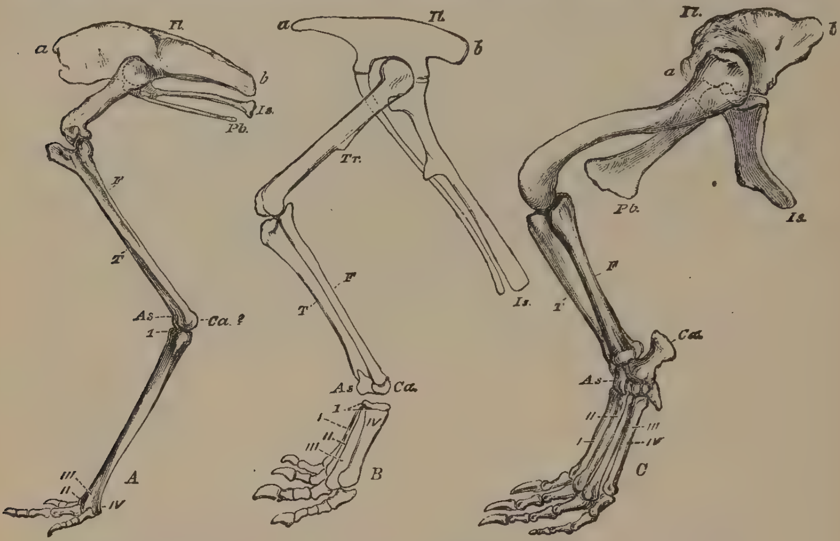

FIG. 698.—*A*, Dromæus; *B*, Dinosaur; *C*, Crocodile: *As*, astragalus; *Ca*, calcaneum.

The *Iguanodon* was one of the best known as well as one of the largest. It was a huge herbivorous Dinosaur, found in the Upper Jurassic and Lower Cretaceous of Europe. It takes its name from the resemblance of its teeth (Fig. 699) to those of an Iguana—a living herbivorous reptile, about four or five feet long, although in other respects there is little affinity. Until recently, only portions of the skeleton were found; but the enormous size of these indicated an animal nearly thirty feet long, and exceeding the weight of an elephant. It was impossible from these to form any idea of its general appearance. In 1880, however, several complete skeletons were found by Dollo in the Wealden* of Belgium, and restored first by Dollo and then more perfectly by Marsh. From these it is learned that the animal certainly walked on its hind-legs, using its powerful tail also as a support; also that the anterior part of its jaws was toothless and covered with horn, so as to form a nipping-beak like a turtle's. Fig. 700 is a restoration by Marsh.

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* The Wealden is a transition between the Jurassic and Cretaceous, sometimes put in the former and sometimes in the latter.

The *Megalosaur* was a somewhat smaller but a more formidable carnivorous reptile, which lived through the whole Jurassic period. Its huge jaws were armed with large, curved, flattened, saber-like teeth. A femur has been found forty-two inches long (Phillips), and a tibia thirty-six inches. The animal was at least thirty feet long (Owen). The Megalosaurs also were bipedal.

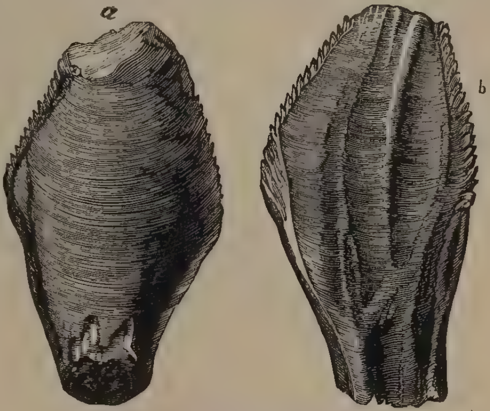

FIG. 699.—Tooth of an Iguanodon.

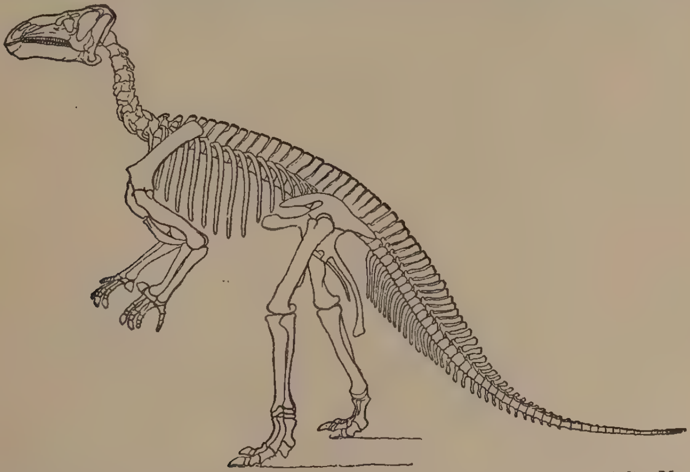

FIG. 700.—Iguanodon Bernissartensis, Boulenger, × $\frac{1}{80}$, Upper Jura, Belgium (after Marsh).

The *Ceteosaur* (whale-lizard) was the largest reptile yet found in Europe, though much larger have been found in the Jurassic of the United States. It has been classed among the Crocodilians, but Prof. Huxley has shown that its true position is among the Dinosaurs. A thigh-bone has been found sixty-four inches long, 27·5 inches in circumference at the shaft, forty-six inches and 44·25 inches in circumference at the two ends respectively. According to Phillips, the animal was at least fifty feet long, ten feet high when standing, and of bulk proportionate. It was like the Iguanodon a vegetable feeder.

The *Hylæosaur* was another herbivorous reptile of the same period. The *Compsognathus* was a carnivorous reptile of smaller size, but of most extraordinary bird-like character, viz., small head, long, flexible neck, large and long hind-leg, and small and short fore-leg. From its structure, it must have walked habitually on its hind-legs alone, and in this position was about two feet high (Fig. 701).

As an example of a European quadrupedal Dinosaur we give a restoration by Marsh of the Scelidosaurus (Fig. 702), an herbivorous Dinosaur allied to the Stegosaur (p. 480).

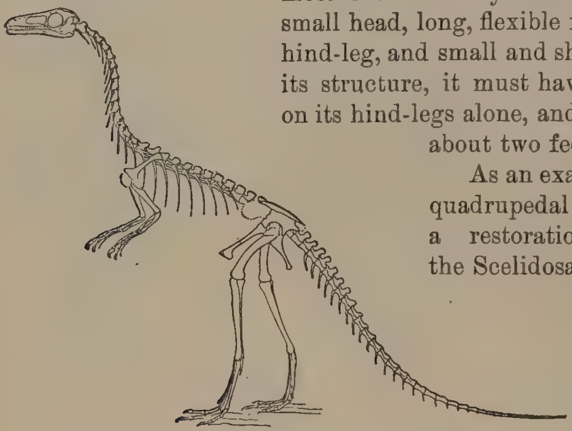

Fig. 701.—Compsognathus (restoration by Marsh).

3. *Pterosaurs.* — These flying reptiles were certainly among the most extraordinary animals that have ever existed. The order includes several genera, but we will describe only the best known, viz., the *Pterodactyl* (wing-finger), and the Rhamphorhynchus (beak-snout).

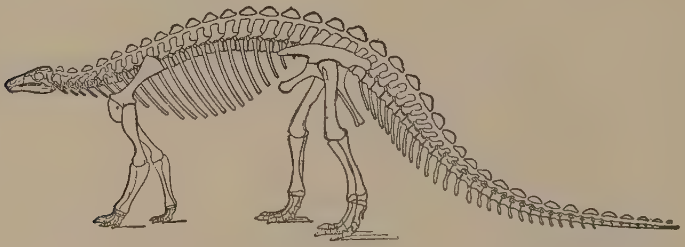

Fig. 702.—Scelidosaurus Harrisonii, Owen, × $\frac{1}{36}$, Jurassic, England (restored by Marsh).

The *Pterodactyl* (Fig. 703) combined the short, compact body; the strong shoulder-girdle, firmly united with the keeled sternum; the short, aborted tail; the long, flexible neck, and hollow, air-filled limb-bones, characteristic of birds—with the head, and jaws, and teeth, of a reptile, and the membranous wings of a bat. In the bat, however, the membrane is supported by *four* fingers, enormously elongated for the purpose, and only one finger is *free* and *clawed ;* while in the Pterodactyl there is only one finger that is enormously elongated and strengthened for the support of the web, and the others are free and clawed.

The *Rhamphorhynchus* differed from the Pterodactyl in having a long tail; and in one species, *R. phyllurus* (Fig. 704) (leaf-tail), this was vertically expanded at the tip so as to act as a rudder in flying.

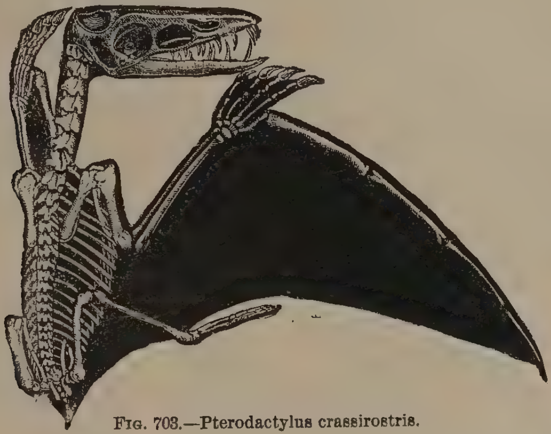

Fig. 703.—Pterodactylus crassirostris.

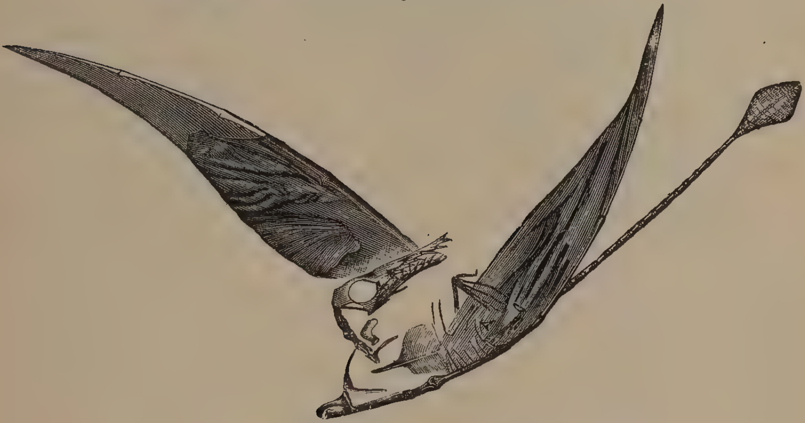

Fig. 704.—Rhamphorhynchus phyllurus (after Marsh).

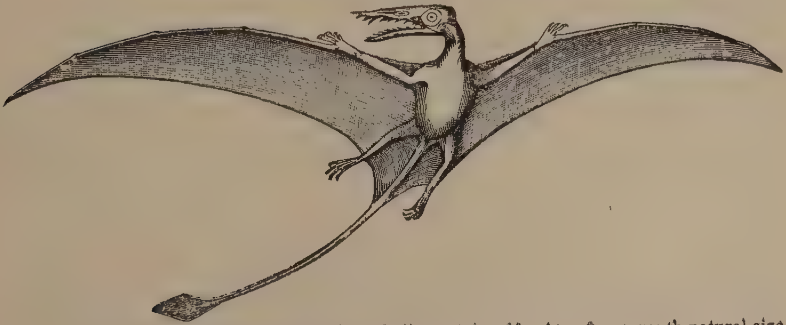

Fig. 705.—Restoration of Rhamphorhynchus phyllurus (after Marsh). One seventh natural size.

In a specimen from the celebrated Solenhofen limestone of Bavaria, and now in possession of Prof. Marsh, even the membranes of the wings were perfectly preserved (Fig. 704). Fig. 705 is a restoration of this species in flight.

The Pterosaurs were of many kinds, which varied in size from two or three feet to eighteen or twenty feet in alar extent.

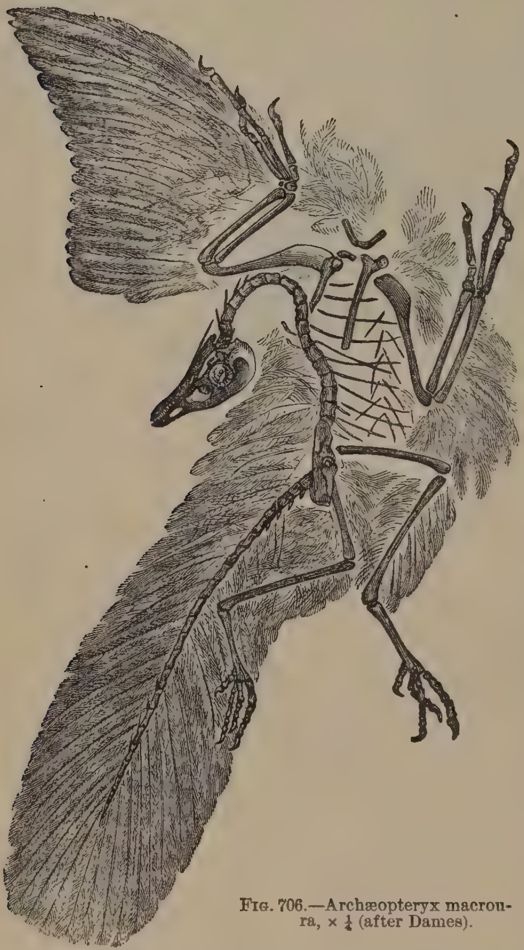
FIG. 706.—Archæopteryx macroura, × ½ (after Dames).

Birds.—The class of Birds is *now* so distinctly separated from all others and the connecting links obliterated, that the earliest birds are of especial interest as throwing light on the evolution of this class. Until 1862 birds had been found only in the Tertiary, and these were already distinctly differentiated as typical birds; but in that year there was found in the Solenhofen limestone, so celebrated for its marvelous preservations of organisms, *a flying feathered biped*, and therefore presumably a bird. But how different from our usual conceptions of this class! Along with its distinctive bird-characters of feet, limb-bones, beak, and especially of feathered wings, it had the *long tail* (Fig. 706) and *toothed jaws* (Fig. 708) of a reptile. The structure of the tail is especially significant. In ordinary birds the tail proper is shortened up to a rudiment, and ends in a large bone, from which radiate the feathers of the *tail-fan*. In this earliest bird, on the contrary, the tail proper is as long as all the rest of the vertebral column put together, consisting, as seen in the figure (Fig. 707), of twenty-one joints from which the fan-feathers come off *in pairs* on each side. The *tail-fan* of this bird differs from that of typical birds precisely as the *tail-fin* of earliest fishes differs from that of typical fishes. The *tail-fan of this earliest bird*, like the *tail-fin* of earliest fishes, was *vertebrated.* This wonderful reptilian bird was called *Archæopteryx* (primordial winged creature), and the species *macroura* (long-tailed).

In 1873 another specimen of Archæopteryx was found in the same locality, and is now in the Berlin Museum. This Berlin specimen has been carefully examined by Vogt, Marsh, and Dames (Figs. 706 and 708). From examination of these two specimens the following singular combination of bird and reptilian characters have been made out. Among bird characters are (1) The strong shoulder-girdle and keeled sternum necessary for flying (but Pterosaurs also have these). (2) A horny beak (but turtles and Rhynchosaurs and some Dinosaurs have this). (3) Tridactyl feet (some Dinosaurs have these). (4) Feathered wings and tail. But, along with these, besides the *toothed jaws* and *long tail* of reptiles, already mentioned, there were also the following characters: 1. The metacarpals and possibly the metatarsals (three in number) were separate, as in reptiles and embryo of birds. 2. The three fingers were all free and armed with claws. In fact, except for the feathers, the fore-limbs were more like legs than wings. 3. The pelvic bones were unconsolidated, as in reptiles and embryo of birds. So complete is the mixture of the two kinds of characters that some zoölogists (Vogt) believe that the reptilian characters predominate, and that it should be called a *bird-like reptile.* Most agree, however, that it is a *reptilian bird.*

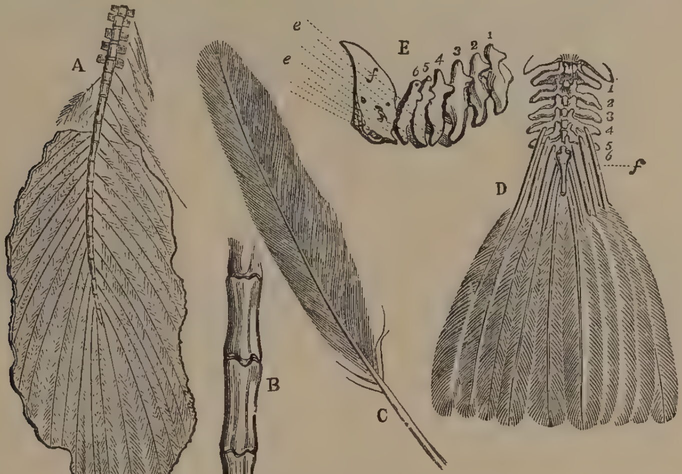

FIG. 707.—A, Tail of Archæopteryx macroura; B, Vertebræ enlarged; C, a Feather; D, Tail of a Vulture; E, side view of the same.

It is interesting to note the different ways in which the same function—that of flying—is effected in different animals, without violating the law of limb-structure. In the Bat the resisting plane is produced by stretching a membrane between the enormously elongated palm-bones and finger-bones; in the Pterodactyl only one finger is enormously enlarged and elongated for this purpose; in the Bird the same bones are shortened and consolidated, and the resisting plane is got by the use of feathers. This was the method also in the Archæopteryx, but the consolidation was not yet complete. Fig. 709 represents wings of these four kinds—the dotted lines run through corresponding parts, and show the identity of structure.

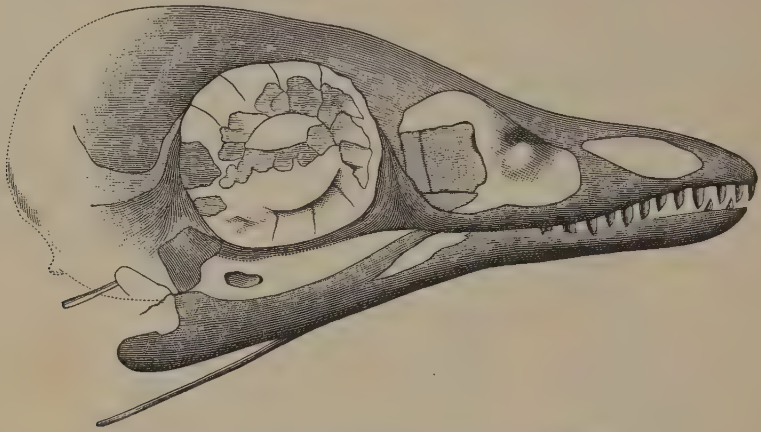

FIG. 708.—Head of Archæopteryx macroura (after Dames).

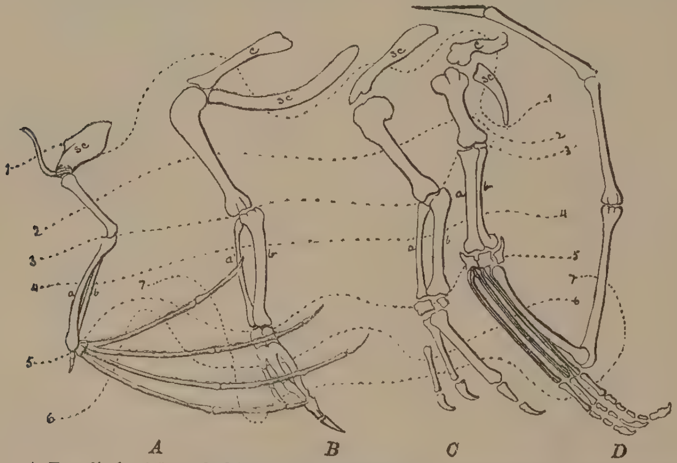

FIG. 709.—*A*, Fore-limb of Bat; *B*, Bird; *C*, Archæopteryx; *D*, Pterodactyl. The dotted lines pass through corresponding parts.

Origin of Birds.—There can be no doubt, then, that *Birds came from Reptiles.* Further, it is most probable that *they came from Dinosaurs.* It is true that Dinosaurs are the largest of reptiles, while birds, with some exceptions, are comparatively small animals; but Marsh has shown that some American Dinosaurs were very small. The *time* of their origin, or separation from the reptilian stem, is still doubtful, but the wonderfully reptilian character of Archæopteryx shows that it can not be far from the point of origin. It was probably *in the Lower Jurassic or Upper Triassic.*

Mammals.—We have already seen (p. 438) that the first appearance of this class was in uppermost Trias; but as these were few in number, and very near the confines of Jurassic, we regarded them as anticipations and put off their discussion. In the Jurassic this anticipation was fully realized. In the same formation (Upper Jurassic) in which we found the old forest-ground (p. 443) have been found also fourteen genera of small mammals. To this may be added five genera from a lower horizon (Stonefield states). If we add to these again fourteen genera (twenty-five species), recently described by Marsh, from the American Jurassic, we have at least thirty-three Jurassic *genera* known. Besides these, at least five genera are found in the Upper Trias of all countries, and sixteen genera (twenty-four species), recently (1889) described by Marsh, from Upper Cretaceous (Laramie). We may say, therefore, that there are now known at least fifty-four *genera* of Mesozoic mammals. The number of *species* is, of course, much greater.

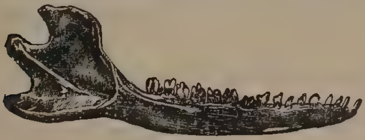

FIG. 710.

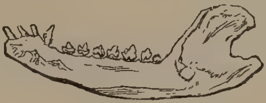

FIG. 711.

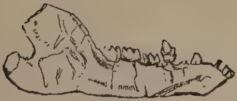

FIG. 712.

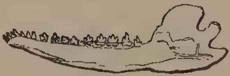

FIG. 713.

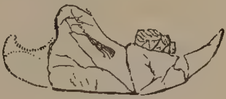

FIG. 714.

FIGS. 710–714.—JURASSIC MAMMALS: 710. Amphitherium Prevostii. 711. Phascolotherium. 712. Amphitherium. 713. Triconodon. 714. Plagiaulax.

Affinities of Jurassic Mammals.—The Jurassic, and indeed the Mesozoic mammals, as contrasted with mammals of later times, may be characterized in a general way as *small insectivorous marsupials*, or, perhaps better, as a type connecting insectivores and marsupials, and therefore lower and more generalized than either. They were, especially the earliest or Triassic, decidedly reptilian in some of their characters. Of these we mention only two.

1. *Teeth.*—A glance at Fig. 715, *a*, in comparison with figure of Theriodont (Fig. 630, *b*), on page 437, shows that the teeth of some of the earliest mammals differed little from those of Theriodont reptiles; in which, as already explained, the tuberculation of the molars characteristic of mammals had already commenced. In the subsequent course of evolution the subordinate cusps of Fig. 715, *a*, *b*, *c*, *d*, *e*, were shifted outward in the upper jaw and inward in the lower jaw, so that the cusps interlocked. This forms the tritubercular molar of Cope (Fig. 715, *f*), so common in Mesozoic animals. From this simple generalized type were afterward developed the more complex molars of the specialized animals of the Tertiary and present time.

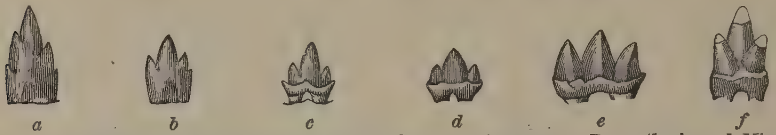

Fig. 715.—A Series of Molars of Triassic and Jurassic Mammals: *a*, Dromatherium; *b*, Microconodon; *c*, Amphilestes; *d*, Phascolotherium; *e*, Triconodon; *f*, Splalacotherium (after Osborn).

2. *Reproduction.*—There seems to be no doubt that many of these animals were marsupials, although more generalized than any existing marsupials. Now, marsupials in their reproduction approach reptiles. In typical mammals the embryo is attached to the mother by the placenta, so that the whole embryonic development is *within* the uterus; in marsupials, on the contrary, there is no placental attachment, and therefore the intra-uterine development is very short and imperfect, and is, in fact, completed *outside* the uterus in the pouch (marsupium). In true mammals the whole embryonic development is *within* (gestation), and the young are born in perfect condition. They are young-bearers (*viviparous*). In birds and reptiles—egg-bearers (*oviparous*)—the whole of the development takes place *without* (incubation). In marsupials the development is *partly within but mostly without.* These, therefore, may be called *semi-oviparous*, or *reptilian mammals.*

Thus the class of mammals has been divided into two sub-classes—*placentals* or *true* mammals, and *non-placentals* or *reptilian* mammals. The latter includes the *marsupials*, semi-oviparous, and the *monotremes* (Ornithorhynchus, Echidna, etc.), which are true egg-layers (oviparous), like birds and reptiles. The non-placentals, with the exception of a few opossums in America, are wholly confined *now* to the Australian region. In Jurassic times they roamed in great numbers all over Europe and America.

Origin of Mammals.—In Theriodonts we see reptiles reaching upward and forward toward mammals. In Jurassic and especially Triassic mammals we see this class reaching downward and backward toward reptiles. But the point of union has not yet been found. The lowest and most reptilian of mammals, the egg-laying monotremes, have not yet *with certainty* been found fossil; but the calcified teeth recently found in the embryo of the Ornithorhynchus so strongly resemble the teeth of one family of Mesozoic mammals—viz., the *Allotheria* (Fig. 848, p. 519)—that it is now believed that these were, indeed, monotremes. It is probable, therefore, that the point of union between the classes reptiles and mammals will be found, not, indeed, in monotremes proper (for these are already specialized), but in a *generalized type connecting monotremes and marsupials.* The time of origin was probably the Lower Trias or Upper Permian. The earliest mammals, such as the Microlestes and the Dromatherium from the American Trias, were not far removed from such a generalized type. The order of evolution has been expressed by Huxley thus: 1. Hypotheria (below mammals); 2. Prototheria (first or lowest mammals); 3. Metatheria (transition mammals); and, 4. Eutheria (perfect or true mammals). The first is represented by the Theromorphs of Permian and Trias, or, better, by a generalized type between these and the monotremes; the second by a hypothetical generalized type connecting monotremes and marsupials of the Triassic; the third by insectivorous marsupials of the Jurassic, and the fourth by the true placentals of the Tertiary. Further, it is probable, as suggested by Osborn,* that the Prototheria of the Triassic separated very early into two branches of Metatheria—one more like the marsupial, the other like insectivora. From the latter came the Eutheria, which again differentiated into many specialized orders.

Mammals, then, existed in considerable numbers in the Jurassic. These, however, were not able to contend with the great Dinosaurs. It was still the age of reptiles. This class not only predominated, but impressed their character on all higher classes. The birds and the mammals were still reptilian. From the reptilian stem the bird and mammal branches were not yet so completely separated that connecting links were obliterated.

SECTION 3.—JURA-TRIAS IN AMERICA.

We have already explained that these two periods are not well separated in America. This is partly on account of the poverty of fossils, and partly on account of the continuity of conditions throughout. It seems best, therefore, in the present state of knowledge to treat them together as one period. Doubtless they will be better separated hereafter.

Distribution of Strata.—1. *Atlantic Border.*—Lying in plication-hollows, or denudation-hollows, unconformably on the gneiss (metamorphic Archæan or Cambrian) of the eastern slope of the Appalachian chain, are found very remarkable isolated patches of sandstones or sandstones and shales, which are referred to this period. These patches are strung along nearly parallel to the chain, and to the coast, from Nova Scotia to the border of South Carolina. They are represented on the map (p. 302) by oblique lines. One of them is found in Prince Edward's Island, another in Nova Scotia; another is the celebrated Connecticut River Valley sandstone; a fourth commences in New Jersey, passes as a narrow strip through Pennsylvania, Maryland, and into Virginia; a fifth and sixth form the Richmond and Piedmont coal-fields of Virginia; a seventh and eighth, the Dan River and Deep River coal-fields of North Carolina. As they are isolated, and without contact with any other formation unless unconformably, their age can not be even conjectured from their stratigraphical relations; but the few fossils which they contain seem to refer them either wholly to the Triassic, or else, more probably, partly to the Triassic and partly to the lower Jurassic.

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* Mesozoic Mammalia, p. 261, Transactions of the Academy of Sciences, Philadelphia, vol. ix, No. 2, 1888.

In connection with nearly all these patches are found columnar trap or dolerite ridges. These are interstratified with the sandstones, and were partly outpoured on the sediments while these were depositing, and partly forced subsequently between the strata (Davis). Mounts Tom and Holyoke are examples in the Connecticut Valley, the Palisades of the Hudson in the New Jersey patch; similar trap-ridges are also found in all the other patches.

2. *Plains and Rocky Mountain Region.*—The geology of this region is still little known, but there seems no doubt that Jura-Trias is widely distributed though largely concealed by subsequent deposits of Cretaceous and Tertiary. They are exposed, however, in narrow bands on the flanks of the Black Hills, the Colorado, Uintah, and Wahsatch Mountains, and over wider areas in Northwest Texas, New Mexico, Arizona, and Utah, where they are called "*Red beds.*" Their outcrop form one of the most conspicuous erosion-cliffs (p. 282) of the region north of Grand Cañon. As may be inferred from their almost universal red color, they are very barren of fossils. The same might be inferred from the presence of great beds of gypsum in the Plateau region and beds of salt in Kansas.

3. *Basin Region and Pacific Border.*—They occur also over all the *western* part of the Basin region. Covered in the valleys by recent deposits, but exposed on the flanks of all the mountains. On both sides of the Sierra and Cascade Ranges they occur as the auriferous slates of California and northward.

Life-System.

The characterization of the life-system of the Jura-Trias period in America is best brought out in connection with a description of some of the more interesting localities and of their remarkable records.

Connecticut River Valley Sandstone—The Strata.—This locality has been made classic ground for the geologist by the indefatigable labors of the late President Hitchcock, of Amherst. The strata border the Connecticut River, on both sides, through the whole of Massachusetts and Connecticut, as far as Middletown, where the river trends to the east while the sandstone area passes straight on to the Sound at New Haven. The whole forms an irregular area about 110 miles long and 20 miles wide. They consist of red sandstones and shales, dipping somewhat regularly to the east, at an angle of about 20° to 30°, indicating a thickness of at least 5,000 feet (Dana) to 10,000 feet (Hitchcock). The general relations of the strata with the intrusive trap and the underlying gneiss are shown in the accompanying figure (716). The trap is seen to be conformable with the strata, but the whole series has been subsequently fissured and faulted in such wise that the strata are repeated and the thickness is apt to be overestimated, as already explained on page 239. The trap-ridges are formed by the outcrop of the tilted and faulted sheets of lava. This regular dipping to the east throughout the whole series can be most easily explained by supposing that at the end of this period the whole area of previously-horizontal strata (Fig. 717, *A*) was lifted into an incline of 20° or more, and afterward cut away by denudation, as shown in the diagram (Fig. 717, *B*). In the elevation the strata were fissured and faulted, as shown in Fig. 716.

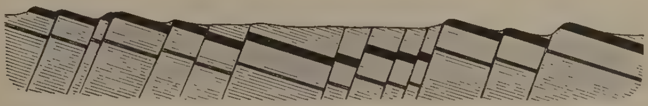

FIG. 716.—General Section across Connecticut River Sandstone (after Davis): The black, trap.

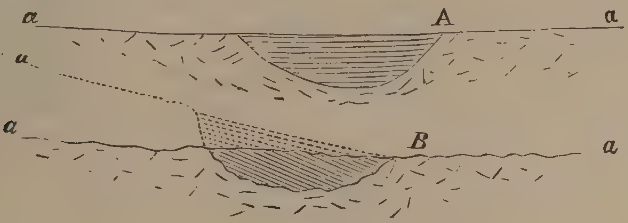

FIG. 717.

The whole series of sandstone is very distinctly stratified, and in many parts beautifully fissile. When these parts are broken open along their lines of lamination, all kinds of *shore-marks* are found in the greatest perfection, viz., *ripple-marks*, *rain-prints*, *sun-cracks*, *leaf-impressions*, and *tracks of animals.* It is evident, therefore, that this was, throughout, a *littoral or shoal-water deposit.* But it is at least 5,000 feet thick. Therefore, there must have been subsidence to that extent. Here, then, we have evidence of *rapid* deposit (for the materials are coarse), invasion of interior heat with *aqueo-igneous fusion*, *subsidence*, formation of *fissures*, and ejection of *lava.*

These sandstones are poor in fossils, but the few that are known indicate the horizon of the Keuper or Upper Triassic of Europe. As these are found near the middle of the series, it is probable that the series represents the whole of the Trias and part of the Juras of Europe.

The Record.—The general *redness* of the sandstone is sufficient evidence that organic remains are very scarce; and so, indeed, we find it.

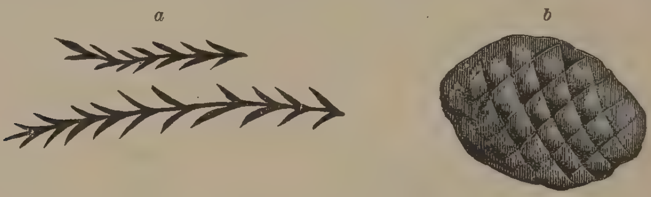

Fig. 718.—*a*, Frond; *b*, Cone (after Hitchcock).

Several species of fishes, a few leaves, the most perfect of which is a species of fern—Clathopteris—and a fir-cone (Fig. 718), and a few small fragments of thin, hollow bones, which may have belonged to either birds or reptiles, are all that until recently had been yet found.

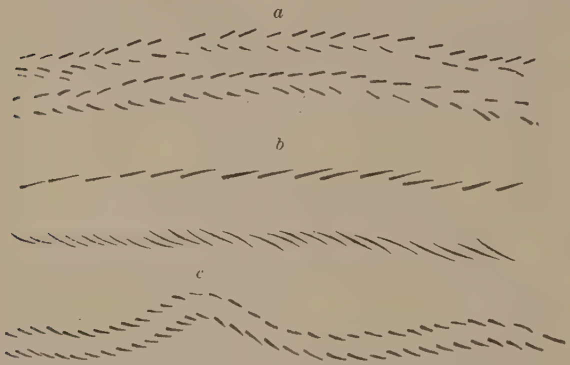

Fig. 719.—*a*, *b*, *c*, Tracks of Insects, Crustacea, or Worms (after Hitchcock).

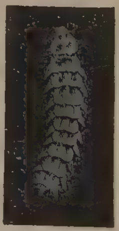

Fig. 720.—Larva of an Ephemera (after Hitchcock).

But by far the most interesting portion of the record in this locality consists of *tracks.* These are partly tracks of Insects and Crustaceans, and partly of Reptiles and, possibly, of Birds. Some of those which have been referred to Crustaceans and Insects are shown in Fig. 719, *a*, *b*, *c*. There has been found, also, the whole form of one insect apparently the larva of an Ephemera (Fig. 720). It is quite probable that many of the tracks were formed by similar larvæ inhabiting the water.

Reptilian Tracks.—By far the larger number of tracks are those of Reptiles. More than fifty species have been described by Hitchcock.* These vary extremely, both in size and in character. In *size*, they vary from the track of a living Triton, a half-inch long, to that of the Otozoum (Fig. 721), twenty inches long, and with a stride of three feet. Some had five toes, some four, and some only three functional toes on the hind-feet. Again, some had hind and fore feet of nearly equal size, and evidently walked or crawled in true quadrupedal style. Others had hind-feet much larger than fore-feet, and were essentially bipedal in locomotion, only putting down their small fore-feet occasionally; but walking bird-like, not hopping kangaroo-like, on their hind-legs. In connection with the bipedal tracks there have been found what seemed to be the impression of a dragging tail (Fig. 722); but these are so rare and doubtful that it is generally believed the animals were mostly long-legged and short-tailed; or else they lifted their tails in walking.

The general conclusion from an attentive study of these tracks, in connection with the findings elsewhere of bones and teeth, is that they are the tracks of Dinosaurs. The hugest among them, the *Otozoum Moodii* (Fig. 721), was probably a long-legged biped Dinosaur, which stood twelve feet high. The *Anomœpus* (Fig. 723), a common form, was also probably a *Dinosaur*, which walked often on two legs only, and in resting brought the whole tarsus and heel on the ground, in the manner of a kangaroo.

The doubts in regard to the character of these reptiles have now been cleared up by the fortunate discovery by Marsh of nearly perfect skeletons. In Fig. 724 we give a restoration of one of these.

Supposed Bird-Tracks.—Those which have been referred to birds are: 1. *Wholly bipedal*, i. e., there is no evidence of fore-feet at all. 2. They are *tridactyl*. 3. They have a regular progression in the number of joints in the tracks, the inner toe having two, the middle toe three, and the outer toe four *joints*. Now, in birds, the inner toe has three, the middle toe four, and the outer toe five joints, but the last two joints in each case make but one division of the track, so that the track is exactly what is given above. The discovery, however, that many Dinosaurs have but three functional toes on the hind-foot, and that they also have the same number of joints as birds, has greatly shaken confidence in the ornithic character of these tracks. Only the absence of fore-feet tracks, therefore, remains. But as many of these early reptiles walked *occasionally* on two legs, it is not impossible that *some* of them *always* walked thus. It is *probable*, therefore, that all these tracks are those of Reptiles. Assuming them to be those of Birds, they vary in size from those of a snipe to those of the great *Brontozoum*, eighteen inches long, and with a stride of four feet (Fig. 725). This huge bird, if bird it was, must have been at least fourteen feet high (Dana). Such a huge animal must have been wingless, like the ostrich, etc., for its size is far beyond the limit within which flight is possible.

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* About seventy species are now known (E. H. Hitchcock).

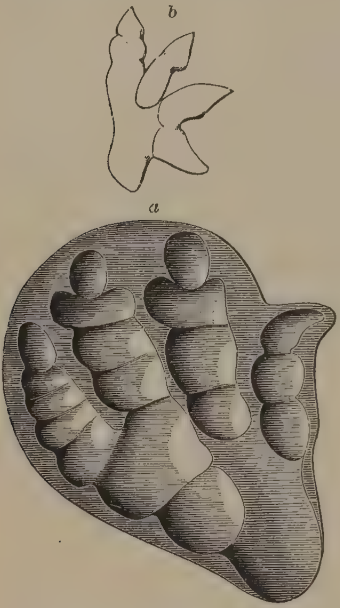


FIG. 721.

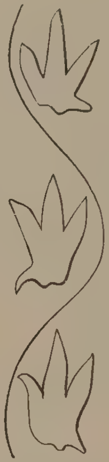


FIG. 722.

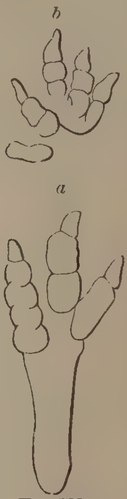


FIG. 723.

FIGS. 721–723.—REPTILE TRACKS (after Hitchcock): 721. Otozoum Moodii: *a*, hind-foot, × $\frac{1}{10}$; *b*, fore-foot, × $\frac{1}{10}$. 722. Gigantitherium caudatum, × $\frac{1}{30}$. 723. Anomœpus minor, × $\frac{1}{8}$: *a*, hind-foot; *b*, fore-foot.

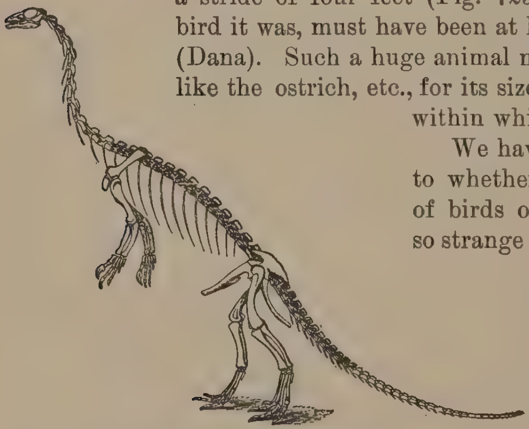


FIG. 724.—Anchisaurus colurus, Marsh, × $\frac{1}{24}$, Triassic, Connecticut (after Marsh).

We have expressed a doubt as to whether these tracks be those of birds or reptiles. This is not so strange as it may at first appear. These two classes are, indeed, *now* very widely separated, but *then* they were very closely allied. There were probably animals then living which, even if we saw them, might puzzle us to decide whether to call them reptilian birds or bird-like reptiles. *These two classes were perhaps not yet fairly disentangled and separated from each other.*

We may easily imagine the circumstances under which these tracks were formed. During the Jura-Trias period there was in the region of the Connecticut Valley a shallow inland sea, connected by a narrow outlet with the ocean. Into this the tides flowed and again ebbed, leaving extensive flats of mud or sand ribbed with ripple-marks. A passing shower pitted the soft mud, and the sun, coming out again from the breaking clouds, dried and cracked it. Huge bird-like reptiles, and possibly reptilian birds, sauntered near the shore-margin in search of food. The tide came in again with its freight of fine sediments, gently covered the tracks, and preserved them forever. This occurred constantly for many ages about the end of the Triassic or the beginning of the Jurassic period, for the tracks are found near the middle of the series of strata.

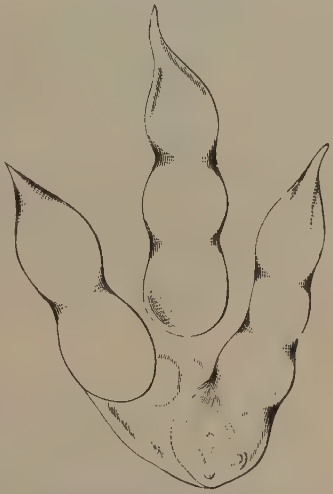


FIG. 725.—Track of Brontozoum giganteum, × ⅛ (after Hitchcock).

Richmond and North Carolina Coal-Fields.—The patches occurring in Virginia and North Carolina are *coal-bearing.* They constitute the Richmond and Piedmont coal-fields of Virginia, and the Deep River and Dan River coal-fields of North Carolina. Fig. 727 gives a generalized section of the Richmond coal-fields taken from Daddow. The strata of this field are sandstone and shales, 700 to 800 feet thick, lying in irregular erosion-hollows of the gneiss. All the

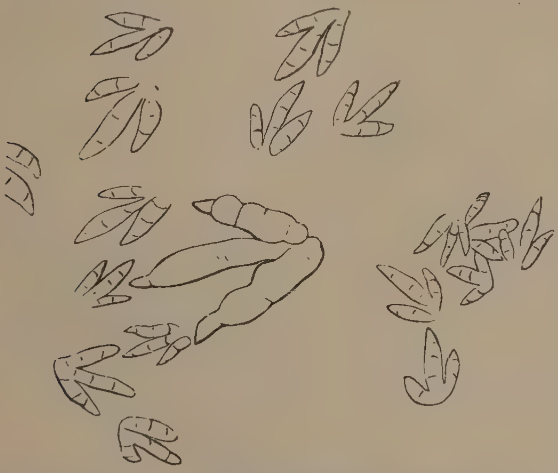


FIG. 726.—Portion of a Slab with Tracks of several Species of Brontozoum (after Hitchcock).

phenomena of a coal-field are here repeated, viz., interstratified seams of *coal* and beds of *iron-ore*, *under-clays* with roots, and *roof-shales* with leaf-impressions. There are several seams of coal, the lowest of which is almost in contact with the gneiss. Some of the seams are of great thickness—thirty to forty feet—and the coal is very pure. It is probable that this coal, like that of the Carboniferous times, was formed in a marsh, which was sometimes converted into a lake. The plants found are very decidedly Upper Triassic and Lower Jurassic, viz., Cycads, Conifers, Equisetæ, and Ferns. Fontaine makes them *Rhætic*, i. e., transitive between Triassic and Jurassic. The animals indicate the same horizon.

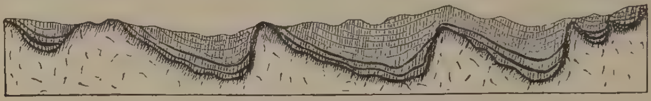


FIG. 727.—Section across Richmond Coal-field (after Daddow).

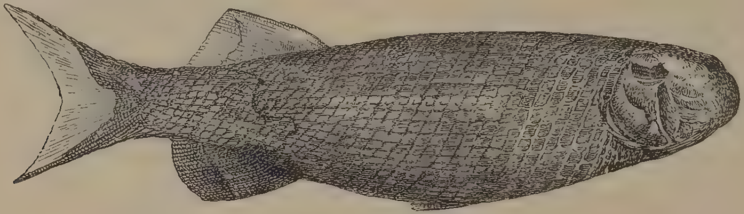
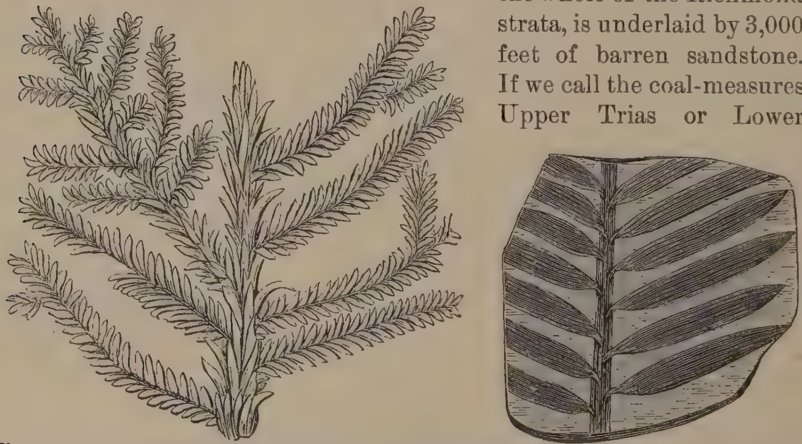


FIG. 728.—Dictyopyge macrura, a Ganoid (after Emmons).

The Deep River and Dan River coal-fields of North Carolina are very similar to those in Eastern Virginia, except that in the Deep River coal-fields the coal-bearing portion, which seems to correspond with the whole of the Richmond strata, is underlaid by 3,000 feet of barren sandstone. If we call the coal-measures Upper Trias or Lower



FIGS. 729, 730.—FOSSILS OF NORTH CAROLINA AND RICHMOND COAL-BASINS (after Emmons): 729. Walchia diffusus. 730. Podozamites Emmonsi.

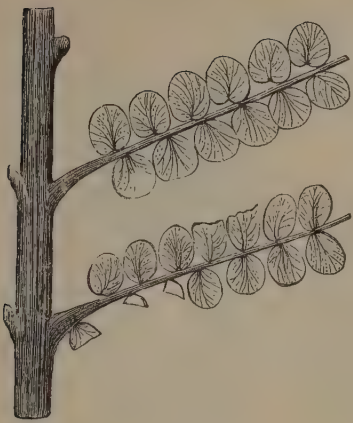


Fig. 731.

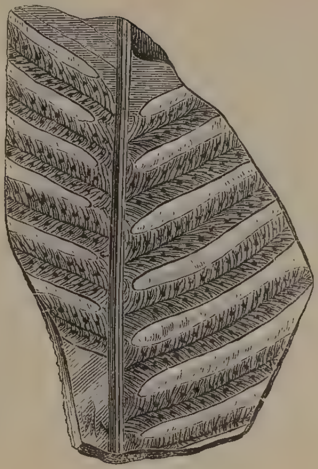


Fig. 732.

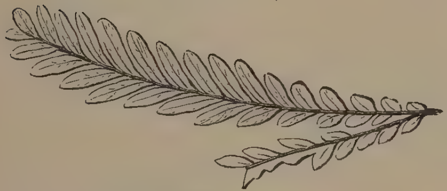


Fig. 733.

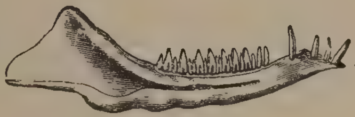


Fig. 734.

Figs. 731–734.—Fossils of North Carolina and Richmond Coal-Basins (after Emmons): 731. Neuropteris linæfolia—Richmond Coal. 732. Pecopteris falcatus. 733. Neuropteris. 734. Jaw of Dromatherium sylvestre.

Juras, these barren sandstones are certainly Triassic. In their upper portion, and therefore probably in the Upper Triassic, Emmons found jaws of a Marsupial, which he names *Dromatherium sylvestre* (Fig. 734). As this is one of the earliest, so it is also one of the most reptilian of mammals. According to Osborn, it had many reptilian characters of teeth, e. g., conical premolars and imperfectly divided fangs, and imperfect cusps in the molars (Fig. 715, *a*) as in the Theromorph reptiles. Until the recent discoveries of Marsh, this, and perhaps another genus from the same place, was the only mammal known from the Jura-Trias of America. We give in Figs. 729, 730 some of the plants and animals of these two basins. Tridactyl tracks like those in Connecticut have also been found in New Jersey and in Pennsylvania.

Other Patches.—In other patches, especially in New Jersey, Pennsylvania, and Nova Scotia, reptilian bones and teeth have been found, representing Dinosaurs and Crocodilians or Lacertians.

Interior Plains and Pacific Slope.—The Jura-Trias of the interior plains are singularly deficient in fossils. The gypsum in many of them furnishes the explanation. They were probably formed in interior and very salt seas, which are usually deficient in life. The two periods are, however, in some places at least, better separated than on the Atlantic slope, probably because of more variable conditions.

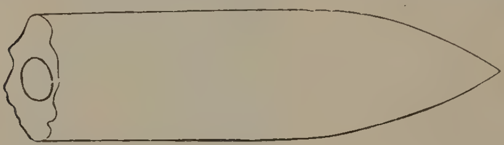


FIG. 735.

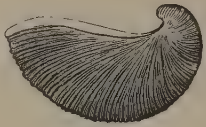


FIG. 736.

FIGS. 735, 736.—JURASSIC FOSSILS OF UTAH (after Meek): 735. Belemnites densus. 736. Gryphæa calceola.

On the slopes of the Black Hills and on the South Platte undoubted Jurassic fossils occur, indicating an open sea. In New Mexico Newberry found impressions of plants, indicating the same horizon as in North Carolina and Virginia—i. e., Upper Triassic. Some of these are given (Figs. 737–744).

On the Pacific coast marine life no doubt abounded, as this was the margin of an open sea; but the rocks here are very highly metamorphic, and the fossils, therefore, mostly destroyed. Wherever this is not the case, the rocks abound in fossils. In Humboldt County, Nevada, for example, the strata in some places seem almost wholly made up of Ceratites Whitneyi (Fig. 747). In the same locality the remains of an Enaliosaur (sea-saurian) have been found. On account of the marine conditions prevalent, the two periods are more easily separable

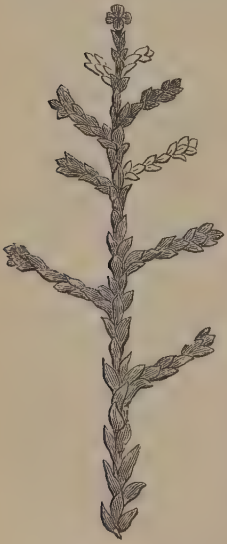


FIG. 737.

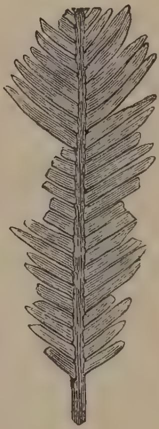


FIG. 740.

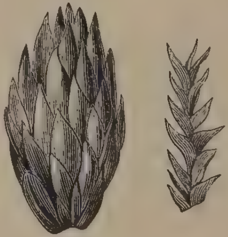


FIG. 739.

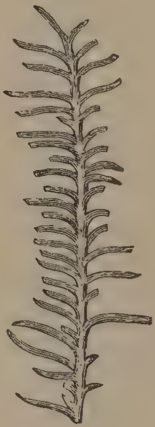


FIG. 738.

FIGS. 737–740.—PLANTS OF THE JURA-TRIAS (after Newberry): 737. Branch of Conifer (Brachyphyllum). 738. Branch of Conifer. 739. Conifer, Branch and Fruit. 740. Zamites occidentalis.

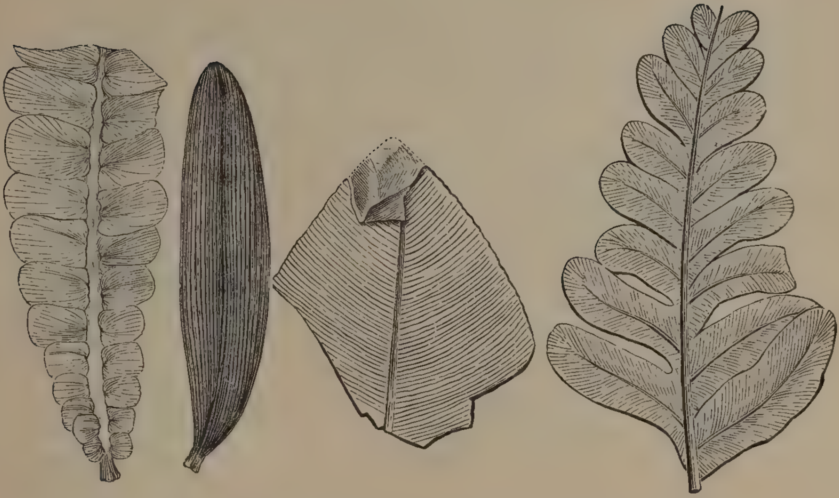


FIG. 741. FIG. 742. FIG. 743. FIG. 744.

FIGS. 741–744.—PLANTS OF THE JURA TRIAS (after Newberry): 741. Otozamites Macombii. 742. Podozamites crassifolia. 743. Tæniopteris elegans. 744. Alethopteris Whitneyi.

on the Pacific coast. In fact, perhaps the completest illustration of the Jura found at all in the United States is that recently discovered by Diller in Northern California.*

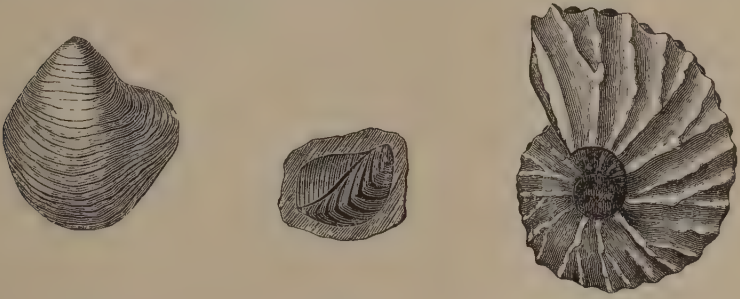


FIG. 745. FIG. 746. FIG. 747.

FIGS. 745–747.—CALIFORNIA JURA-TRIAS SHELLS: 745. Gryphæa speciosa (after Gabb). 746. Trigonia pandicosta (after Gabb). 747. Ceratites Whitneyi (after Gabb).

Recent Discoveries.—Very recently in Colorado and Wyoming, in beds which are referred to the uppermost Jurassic, a large number of most extraordinary reptiles have been found and described by Marsh and Cope. Also, in the Wyoming beds, Marsh has discovered some twenty-five species of Marsupial mammals and a reptilian bird (*Laopteryx*). The beds from which all these have been taken are called, from their most abundant and characteristic form, the *Atlantosaur*

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* American Geologist, vol. x, p. 83, 1892.

beds. These discoveries are treated separately, not only on account of their great importance, but also and especially because they belong to an entirely different horizon, viz., the uppermost Jurassic, passing into the Cretaceous.*

Dinosuors.—The most abundant and the largest reptiles found here are Dinosaurs. Some ten or twelve species of this order have been described by Cope, and thirty or forty species by Marsh. Some of these are from the east slope of the Colorado Mountains, but the most important have been found on the west slope. In the museum of Yale College there are now the remains of several hundred individuals. These American Jurassic Dinosaurs were probably the largest land animals that have ever lived. Cope describes one (Camarasaurus) with a thigh-bone six feet long, and Marsh describes one (Atlantosaurus immanis) with a thigh-bone of still greater length. Along with these huge animals lived also the smallest Dinosaurs yet known—one of them, Nanosaurus agilis, being about half the size of a common fowl.

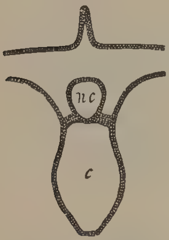

FIG. 748.—Dorsal vertebra of *Cœlurus fragilis*, transverse section (after Marsh).

The characteristics of these ancient reptiles have been worked out with great skill by Marsh, according to whom the vertebræ of many of them were full of large cavities, so as to make these enormous bones as light as possible. This character reached its highest expression in *Cœluria* of Marsh (Fig. 748).

The American Dinosaurs were not only remarkable for their size and number but also for their great variety of forms. According to Marsh, some of them were reptile-footed (*Sauropoda*), some beast-footed (*Theropoda*), some bird-footed (*Ornithopoda*), and some belonged to a most remarkable family, *Stegosauria* (plate-covered Saurians), not previously recognized.

The *Sauropoda* were the hugest of all. They were *five-toed*, *plantigrade*, and *quadrupedal.* Their large limb-bones (Fig. 749) and massive pelvis (Fig. 750) show that they walked with the body well lifted from the ground (Fig. 751). They were all herbivorous. Good examples of these are seen in the *Atlantosaurus* (a thigh of which was found more than six feet long and twenty-five inches thick, the animal itself being probably seventy or eighty feet long); the *Brontosaurus*, sixty feet long (Fig. 751); and the *Morosaurus* (Fig. 749, 750). The restoration of the Brontosaurus (Fig. 751) shows the ex-

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* The Atlantosaur beds are classed with the Jurassic, mainly because their vertebrate fauna is of this period, and partly because of the great gap between it and the Dakota Cretaceous. The question whether they should be called uppermost Jurassic or lowermost Cretaceous has, however, been raised by some geologists. They apparently correspond to the Wealden, which many geologists class with the Cretaceous. Marsh, however, regards them as decidedly Jurassic.

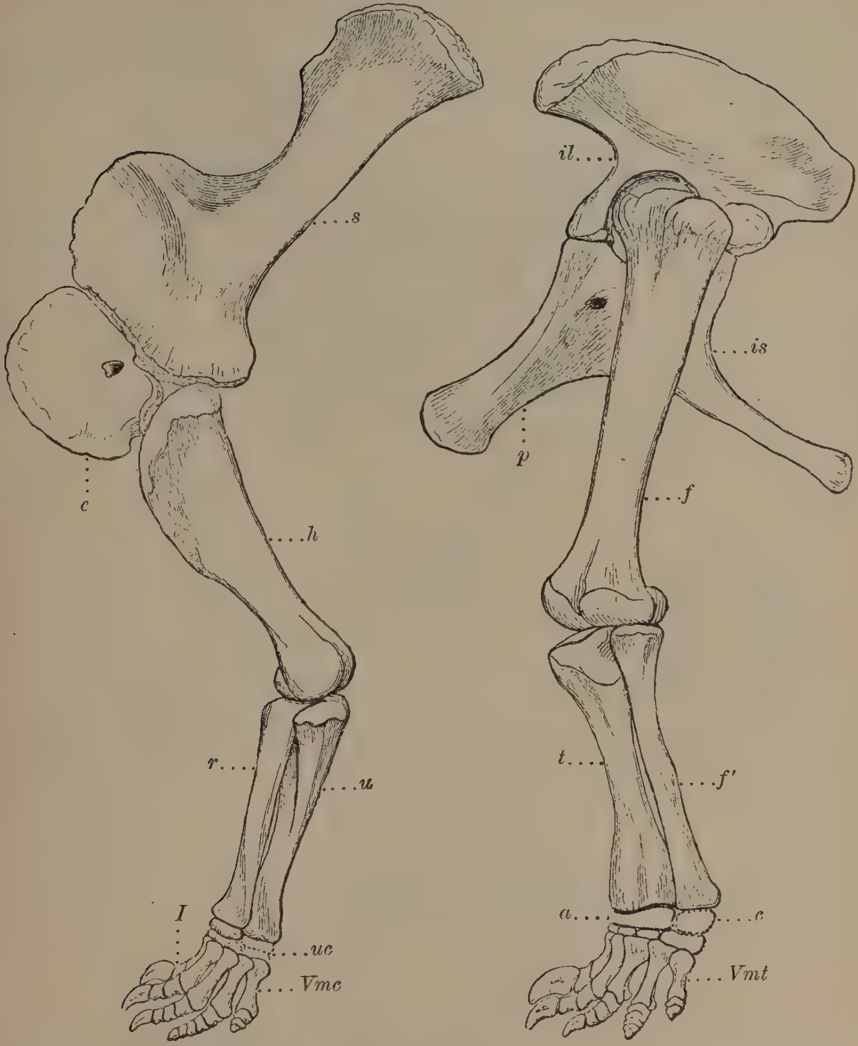

Fig. 749.—1. Bones of left fore-leg of Morosaurus grandis (after Marsh). One twentieth natural size. *s*, scapula; *c*, coracoid; *h*, humerus; *r*, radius; *u*, ulna; *uc*, ulnar carpal; *I*, first metacarpal; *Vmc*, fifth metacarpal. 2. Bones of left hind-leg of Morosaurus grandis. One twentieth natural size. *il*, ilium; *is*, ischium; *p*, pubis; *f*, femur; *t*, tibia; *f′*, fibula; *a*, astragalus; *c*, calcaneum; *Vmt*, fifth metatarsal.

treme smallness of the animal's head, and the brain-cavity shows a still more remarkable smallness of the brain.

The *Theropoda* included, among foreign representatives, the Megalosaur and Compsognathus, already figured (p. 460), and among American genera Anchisaurus (p. 472) and Ceratosaurus (Fig. 752). They were *four- to five-toed*, *digitigrade*, and *bipedal*. This is shown by the disparity in size of hind and fore limbs. They were carnivorous.

The *Ornithopoda* included, among foreign representatives, the Iguanodon, already figured (p. 459), and Hypsilophodon (Fig. 819, p. 503), together with many American genera, such as *Laosaurus* (Fig. 753) and *Camptosaurus* (Fig. 754), *Claosaurus* (Fig. 847, p. 518), etc. They were *three-toed*, *digitigrade*, *bipedal* herbivores.

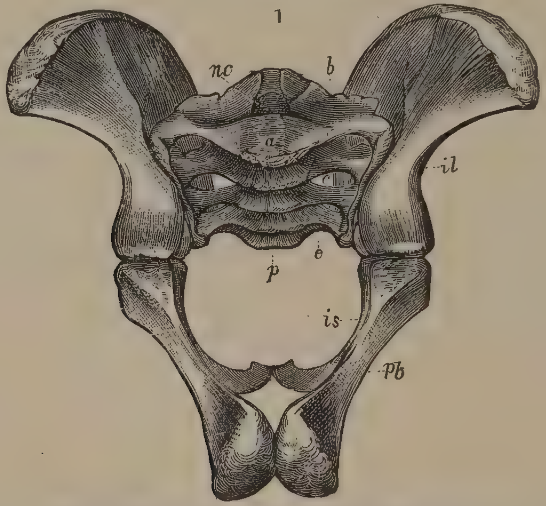

Fig. 750.—Pelvic arch of Morosaurus grandis (after Marsh), seen from in front. One sixteenth natural size: *a*, first sacral vertebra; *b*, transverse process of first sacral vertebra; *c*, transverse process of second vertebra; *p*, fourth or last sacral vertebra; *nc*, neural canal; *il*, ilium; *is*, ischium; *pb*, pubis.

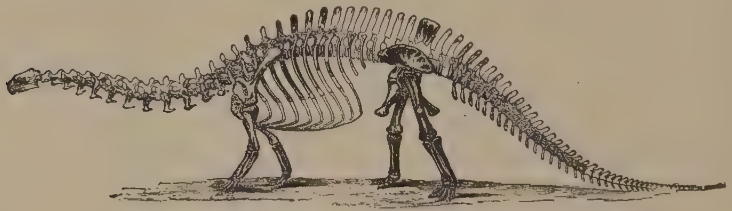

Fig. 751.—Brontosaurus excelsis, × $\frac{1}{120}$ (restored by Marsh).

The *Stegosaurs* were perhaps the most remarkable of all. The restoration of this strange animal (Fig. 755) shows a series of broad plates rising three feet high along the whole dorsal ridge and becoming double near the end of the tail. The use of these extraordinary appendages it is difficult to conceive. In spite of the great disparity in the length of the hind and fore limbs, Marsh regards them as quadrupedal. The brains of all Jurassic Dinosaurs were very small in comparison with living reptiles, but this was especially true of Stegosaurs.

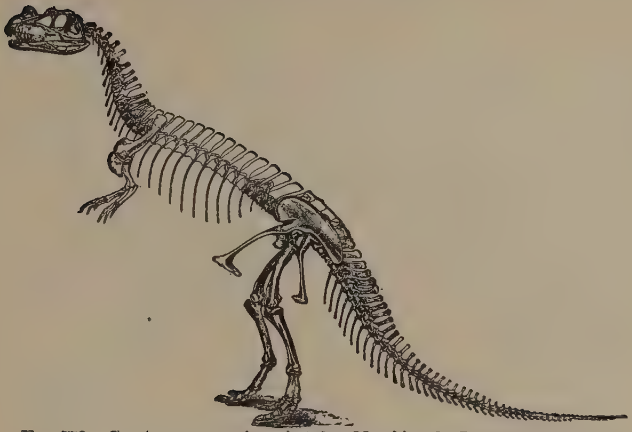

FIG. 752.—Ceratosaurus nasicornis (after Marsh), × $\frac{1}{30}$, Jurassic, Colorado.

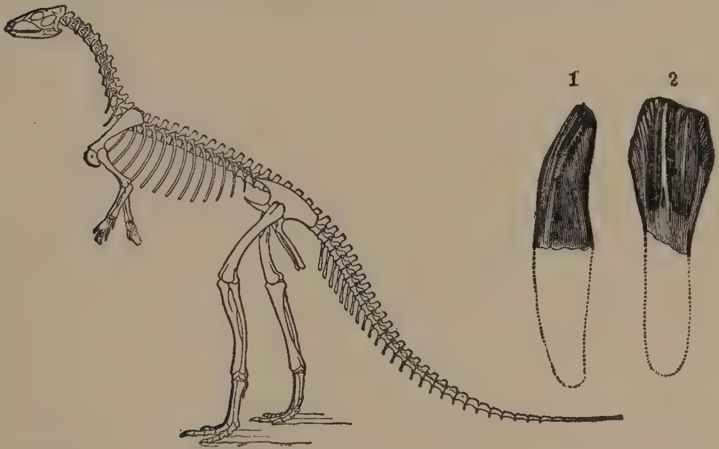

FIG. 753.—Restoration of Laosaurus by Marsh, $\frac{1}{20}$. 1. Tooth of Laosaurus altus (after Marsh), front view. 2. The same, side view. Both twice natural size.

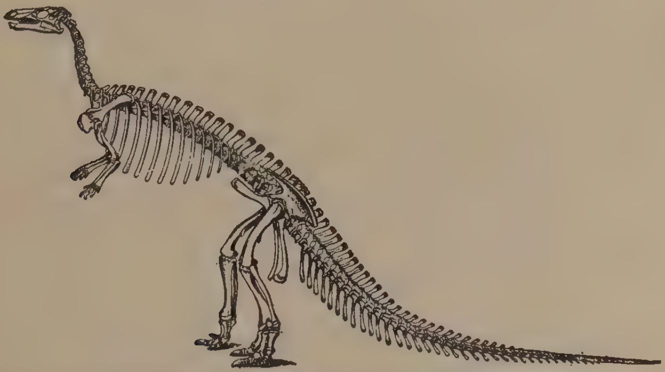

FIG. 754.—Camptosaurus dispar (restored by Marsh), × $\frac{1}{30}$, Jurassic, Wyoming.

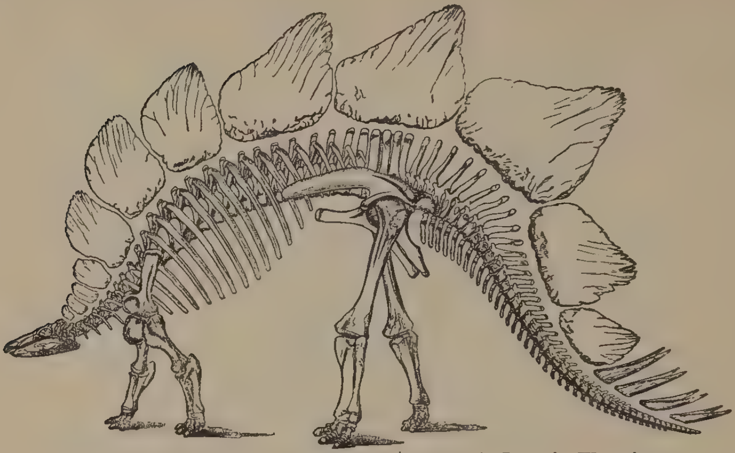

FIG. 755.—Stegosaurus ungulatus (after Marsh), × $\frac{1}{80}$, Jurassic, Wyoming.

To make up for this deficiency they had an enormous enlargement of the spinal cord in the sacral region. This sacral brain—if we may so call it—was ten to twenty times bigger than the cranial brain (Fig. 756). It was necessary in order to work the powerful hind-legs and tail.

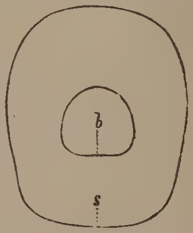

FIG. 756.—Outlines representing transverse sections through brain of Stegosaurus ungulatus, and sacral cavity: *b*, brain; *s*, sacral cavity. One fourth natural size (after Marsh).

Ichthyosaurs and Plesiosaurs.—Besides the Dinosaurs, Marsh describes from the same formation (Jurassic), but from a lower horizon, an Ichthyosaurian, but differing entirely from the Ichthyosaurus of the European Jurassic in being *toothless.* On this account he calls the genus *Baptanodon* (Fig. 757). This reptile had six digits in both fore and hind feet. Also the fore-arm is not distinctly differentiated from the Carpus. It is therefore a more generalized or else a more degraded form than the Ichthyosaurus. In the same beds also he has recently found remains of a Plesiosaur, the first yet found below the Cretaceous in America.

Birds.—In 1881 Marsh discovered in the same beds, the Atlantosaur beds of Wyoming, a Jurassic bird (Laopteryx), the only one yet known in America. It was undoubtedly a reptilian bird, probably with *teeth* and *bi-con-*

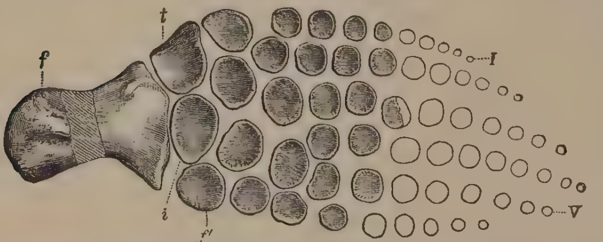

FIG. 757.—Left hind-paddle of Baptanodon discus (after Marsh), seen from below. One eighth natural size: *f*, femur; *t*, tibia; *i*, fibula; *I*, first digit; *V*, fifth digit.

cave vertebræ; but the remains are too imperfect to permit distinct characterization.

Mammals.—Lastly, in the same beds, Marsh has discovered some twenty-five species of small mammals. According to him, these early mammals were not typical Marsupials, but a generalized type connecting that order with Insectivora. He makes of them two suborders, Pantotheria and Allotheria. Figs. 758 and 759 are representatives of these two types. According to Zittell, the Allotheria were probably monotremes, and therefore egg-layers.

Physical Geography of the American Continent during the Jura-Trias Period.—During Palæozoic times the Atlantic shore-line was certainly farther east than it was *subsequently*, probably farther east than it is *now* (p. 303). At the end of the Palæozoic occurred the Appalachian revolution. Coincidently with the up-pushing of the Appalachian chain, the sea-border probably went downward, and the shore-line advanced westward on the land which previously had extended to the submerged continental border. During the Jura-Trias the shore-line to the north was still beyond what it is now, for no Atlantic border deposit is visible; and along the Middle and Southern States it was certainly beyond the bounding-line of Tertiary and Cretaceous (see map, p. 302), for all the Atlantic deposits of this age have been covered by subsequent strata; and yet probably not much beyond, for some of these Jura-Trias patches seem to have been in tidal connection

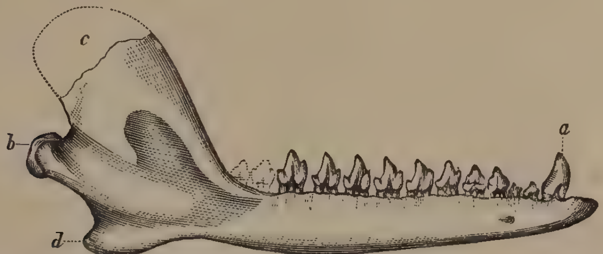

FIG. 758.—Right lower jaw of Diplocynodon victor (after Marsh), outside view. Twice natural size: *a*, canine; *b*, condyle; *c*, coronoid process; *d*, angle.

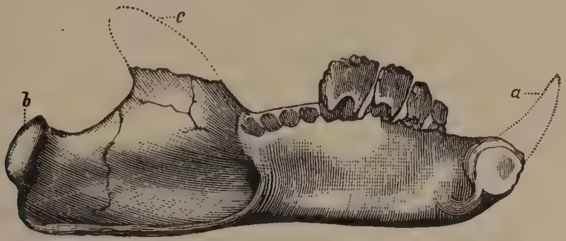

FIG. 759.—Left lower jaw of Ctenacodon serratus (after Marsh), inner view. Four times natural size

with the Atlantic Ocean. It is probable, therefore, that the shore-line was a little beyond the present New England shore-line, and a little within the present shore-line of the Middle and Southern Atlantic States.

A little back from this shore-line, and at the foot of the then Appalachian chain, there was a series of old erosion or plication hollows stretching parallel to the chain. The northern ones had been brought down to the sea-level, and the tides regularly ebbed and flowed there then as in the bay of San Francisco, or Puget Sound, at the present time. In the waters of these bays lived swimming Reptiles, Crocodilian and Lacertian, and on their flat, muddy shores walked great bird-like Reptiles, and possibly reptilian Birds. The more southern hollows seemed to have been above the sea-level, and were alternately coal-marsh and estuary or lake, emptying into the Atlantic. Since that time the coast has risen 200 or 300 feet, and these patches are therefore elevated so much above the sea-level.

Meanwhile, somewhat similar changes were going on in the western portion of the continent. During Palæozoic times, the Pacific shore-line was just east of the Sierra Range, and the place of this range was a marginal sea-bottom. At the end of the Palæozoic, coincidently with Appalachian revolution already explained (p. 424), the Utah Basin region was elevated and became land, while the Nevada Basin region subsided, and the Pacific shore-line advanced eastward to Battle Mountain. But the whole area between this Basin region continent and the Palæozoic area of eastern North America, including the Plateau region and the Plains region, was covered by one or more shallow inland seas, with imperfect connection, or none at all, with the ocean, and in which, therefore, gypsum and salt deposited by evaporation. At least once during Jurassic times this inland sea became broadly connected with the ocean, so that oceanic conditions prevailed. The place now occupied by the Wahsatch Mountains was *then a marginal sea-bottom*, bordering the Basin region continent. On the west the Pacific shore-line was some distance east of the Sierra, and the place of that range was still a sea-bottom, though not so closely marginal as in Palæozoic times.

Disturbances which closed the Period.—This long Jura-Trias period was close, and the Cretaceous period inaugurated, by the *Sierra revolution*, by which the sediments accumulated along the then Pacific shore-bottom, yielding to the lateral pressure, were mashed together and swollen up into the Sierra and Cascade Ranges, and the coast-line transferred westward to the other side of these ranges. Probably at the same time some changes occurred in the region of the Coast Range by which islands were formed off the then coast. Coincidently with these changes probably occurred on the Atlantic slope the elevation of the

Jura-Trias sounds and the outbursts of igneous matter, forming the trap-ridges already spoken of (pp. 468 and 469). Extensive changes also occur at the same time over the whole region of the inland seas, by subsidence and the inauguration of oceanic conditions, which continued to prevail during the Cretaceous. There is reason to believe also that many of the Basin ranges were formed at this time (King), although their present forms as well as that of the Sierra were given much later (p. 276). It was essentially a period of mountain-making in the western part of the American Continent.

SECTION 4.—CRETACEOUS PERIOD.

The most general characteristic of this period is its transitional character. In it Mesozoic types are passing out, and Cenozoic or modern types are coming in, and the two types therefore coexist side by side. In most places in America the Cretaceous lie unconformably on the Jurassic or still lower rocks.

Rock-System—Area in America.—1. On the *Atlantic border* going southward, we find no Cretaceous rocks (except a little patch on Martha's Vineyard) until we reach New Jersey. Here we find a narrow strip peeping out from under the edge of the overlying Tertiary, and marked on the map (p. 302) by oblique interrupted lines. This strip passes through New Jersey, Delaware, Maryland, to the borders of Virginia. Passing south, we find no continuous area until we reach Georgia; yet it underlies the Tertiary in all this region, as is shown by the fact that the rivers in North and South Carolina cut through the Tertiary and expose the Cretaceous in many places. 2. The *Gulf-border* Cretaceous commences in Western Middle Georgia, covers all the prairie region of Middle Alabama, the northeastern or prairie region of Mississippi, then runs northward as a narrow strip through Tennessee nearly to the mouth of the Ohio. It then disappears beneath the Tertiary, to reappear as an area bordering the Gulf Tertiary on the west side. 3. *On the interior plains*, the Cretaceous connecting with the Gulf-border area stretches northwestward to arctic regions, occupying nearly the whole of the great, grassy, level Western Plains called *Prairies*—though much of it is overlaid by the subsequent Tertiary. 4. *In the Rocky Mountain* region Cretaceous strata occupy all the Plateau region—i. e., the region between the Eastern range and the Wahsatch range, except where overlaid by Tertiary or removed by erosion. Recent investigations in Mexico* render it probable that this area stretches also westward through Northern Mexico to the Pacific. 5. On the *Pacific border*, Cretaceous strata form a large part of the Coast Ranges, and also in places the lowest western foot-hills of the Sierra Range. Whitney has estimated the thickness of the Cretaceous rocks in portions of the Coast Range as 20,000 feet, and Diller, 30,000 feet.

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* American Journal of Science, vol. x, p. 386, 1875.

Physical Geography in America.—It is not difficult from the Cretaceous area just given to reconstruct approximately the physical geography. At that time the *Atlantic shore-line* in all the *northern* portion of the continent was farther *out* or *east* than now, for the Cretaceous of this part is all now covered by sea. From New Jersey southward the shore-line was then farther *in* or *west* than now. From Maryland to Georgia the shore-line, though farther *in* than now, was farther *out* than during the Tertiary, as the Cretaceous is covered by the later deposits. *The Gulf* was much more extended both northward and westward than either now or in Tertiary times, its shore-line being along the extreme limit of the Cretaceous of this region. From the Gulf there extended northwestward an immensely *wide sea*, covering the Plains region and the Rocky Mountain region as far westward as the Wahsatch Range, and dividing the continent into two continents, an eastern or Appalachian, and a western or Basin region continent. The place of the Wahsatch range was then the *marginal bottom* of this interior Cretaceous sea. The Pacific Ocean at that time washed against the foot-hills of the Sierra Range, the place of the Coast Range being thus its *marginal bottom.* These facts are represented in the accompanying map.

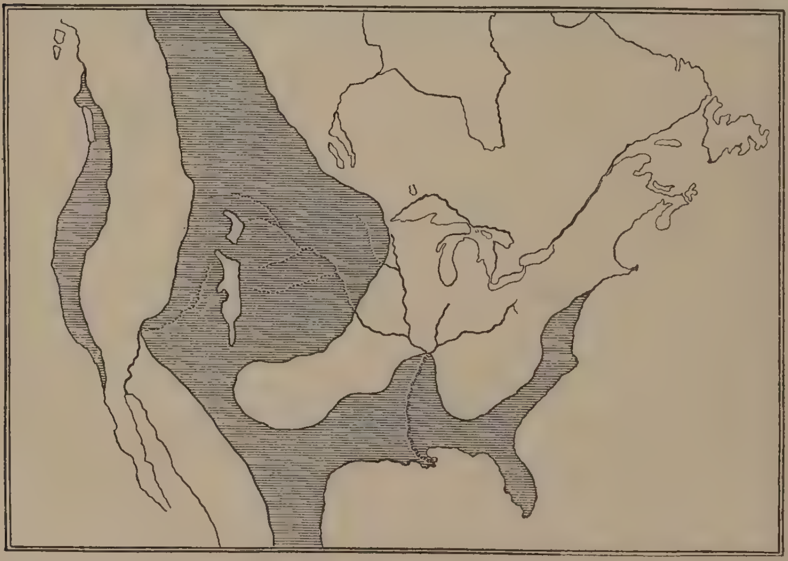

FIG. 760.—Map of American Continent in later Cretaceous Times, shaded part covered with water.

Rocks.—The rocks of the Cretaceous period consist of sands, and clays, and limestones, as in other periods, but, as a whole, are less frequently metamorphic than in the older rocks. There is, however, one kind of rock found in this age in Europe, and also recently in America, which is so peculiar and so interesting that it must not be passed over in silence. We refer to the white *chalk* of England and France, from which the formation and the period take their name, "*Cretaceous.*"

Chalk.—Chalk is a *soft*, *white*, *pure carbonate of lime.* Scattered through the soft mass are found very characteristic nodules of pure flint. These nodules are of various sizes and shapes, sometimes scattered *irregularly*, sometimes arranged in *layers.* Often some fossil, especially a sponge, forms the nucleus around which the aggregation of the silicious matter takes place. On account of its extreme softness, chalk is often sculptured by erosive agencies into fantastic cliffs and needles (Fig. 761).

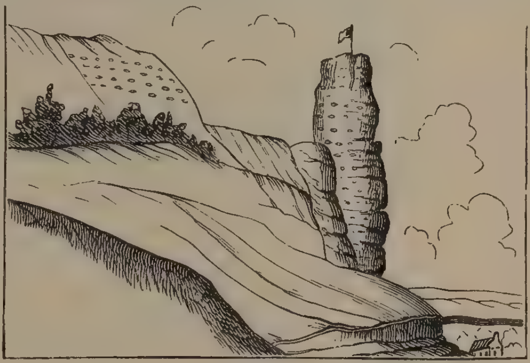
Fig. 761.—Chalk-Cliffs with Flint-Nodules.

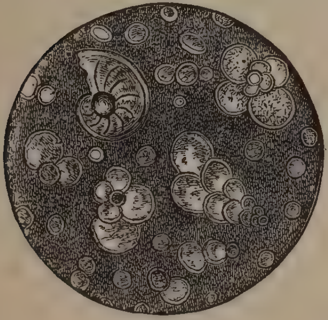
Fig. 762.

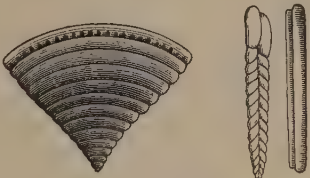
Fig. 763.

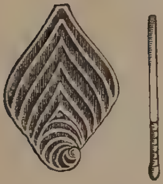
Fig. 764.

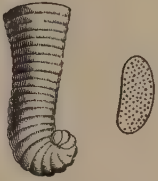
Fig. 765.

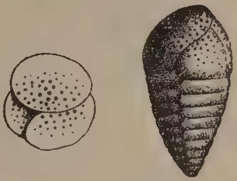
Fig. 766.

Figs. 762-766.—Foraminifera of Chalk: 762. Chalk as seen under the Microscope (after Nicholson). 763. Cuneolina pavonia. 764. Flabellina rugosa. 765. Lituola nautiloides. 766. Chrysalidina gradata (after D'Orbigny).

Examined with the microscope, chalk is found to be composed largely of Rhizopod shells, and of Coccoliths and Coccospheres (supposed shells of unicelled plants), some perfect, more broken, most of all completely disintegrated (Fig. 762). The flint-nodules, similarly examined by section, show spicules of sponge and silicious shells of *Diatoms.* Chalk such as described was supposed to be found nowhere except in Europe, but recently good chalk composed of Foraminiferal shells, and containing flints, has been found in Texas (Hill), and in Kansas and northward to Dakota. We give in Fig. 767 a microscopic view of American chalk. Figs. 763–766 represent some of the more common Rhizopods found in chalk of Europe, and Fig. 768 of those from the chalk of United States.

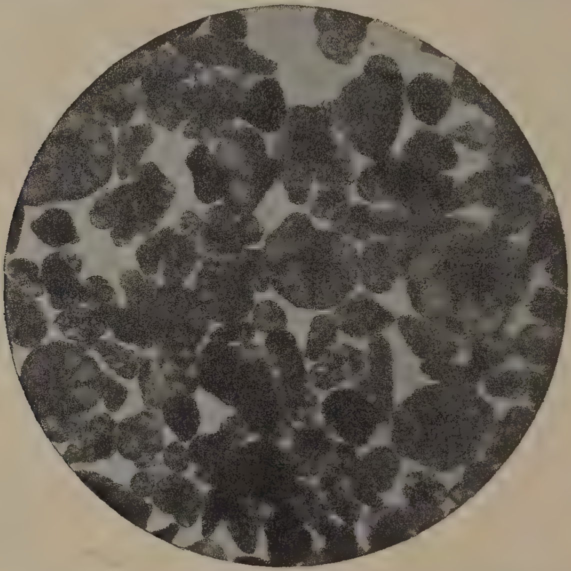

FIG. 767.—View of Iowa Chalk under the microscope (after Calvin).

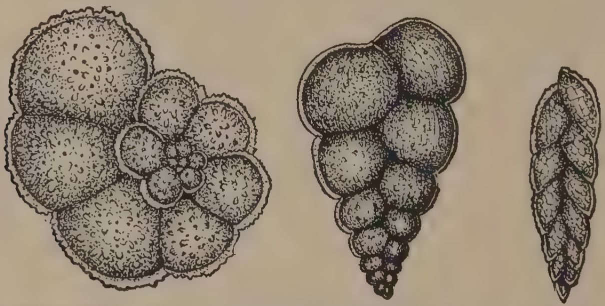

FIG. 768.—Foraminifera from the Chalk of Iowa, × 100 (after Calvin): *a*, Globigerina cretacea; *b*, Textularia globulosa; *c*, Bulimina sp?.

Origin of Chalk.—A material so unique must have been formed under peculiar conditions. Recent investigations have shown that chalk is a *deep-sea ooze.* In all the deep-sea soundings and dredgings recently undertaken, it is found that the sea-bottom between the depths of 3,000 and 20,000 feet, where not too cold, is a white ooze, consisting mainly of Rhizopod shells (Globigerina, Radiolaria, etc.) and Coccoliths, Coccospheres, etc., through which are scattered silicious shells of Diatoms (p. 169). These shells are in every stage of change: some living or at least still retaining sarcode; some perfect, though dead and empty; some broken; most of them completely disintegrated into an impalpable mud. From the great abundance of one genus of Rhizopods, this calcareous mud has been called *Globigerina ooze.* In deep-sea bottoms, therefore, chalk is *now* forming. Also, strange to say, many Sponges, and Starfishes, and Echinoids, and Crustaceans, *very similar to those found in the chalk of Cretaceous times*, have been brought up from present deep-sea bottoms.

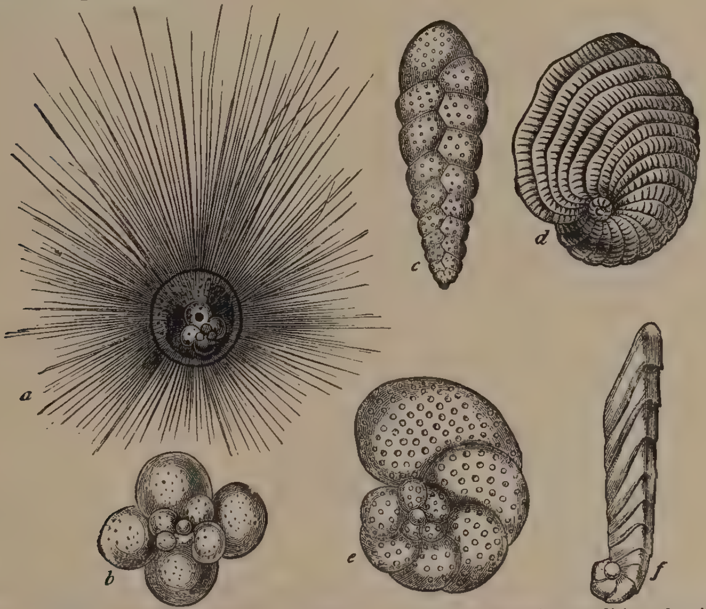

Fig. 769.—Shells of Living Foraminifera: *a*, Orbulina universa, in its perfect condition, showing the tubular spines which radiate from the surface of the shell; *b*, Globigerina bulloides, in its ordinary condition, the thin hollow spines which are attached to the shell when perfect having been broken off; *c*, Textularia variabilis; *d*, Peneroplis planatus; *e*, Rotalia concamerata; *f*, Cristellaria subarcuatula. (Fig. *a* is after Wyville Thomson; the others are after Williamson. All the figures are greatly enlarged.)

There seems little doubt, therefore, that chalk is a deep-sea formation. The flint-nodules have been formed by a subsequent process similar to that which gives rise to other nodules (p. 196). The silica, which in the ooze was at first scattered, is slowly aggregated into pure flint-nodules, and the matrix is left in a condition of pure carbonate of lime.* Probably in most cases some organism formed the nidus about which the silica collected, and organic decomposition was at least one agent in the process.

Extent of Chalk Seas of Cretaceous Times in Europe.—Chalk of nearly homogeneous aspect prevails from the north of Ireland through Middle Europe to the Crimean and Caucasus,† a distance of 1,140 miles; and, in the other direction, from the south of Sweden to the south of Bordeaux, a distance of 840 miles (Lyell). It is evident, therefore, that at that time a deep sea occupied a large portion of Central Europe. The white chalk of England and France is about 1,000 feet thick. When we remember the mode in which it has been formed, this thickness indicates an almost inconceivable lapse of time.

Cretaceous Coal.—Coal is again found in large quantities in rocks of this period in the United States. The mode of occurrence is similar to that found in rocks of other periods; but as most of this coal is found in the Laramie, and as this is a *transition* group to the Tertiary, we shall put off the discussion to the end of the Cretaceous.

Subdivisions of the Cretaceous.—In the localities where the American Cretaceous was first well studied, viz., in New Jersey and in the Western Plains and Plateau region, the lower part of the series was wanting, and hence a great gap was supposed to exist here in the American geological record. But recently the Lower Cretaceous has been found in many widely-separated regions and by different observers, viz., in California, by Whitney (Shasta group); in Texas, by Hill (Comanche group); ‡ in Canada, by Dawson (Kootanie group); and on the Atlantic border, by McGee (Potomac group).# The Comanche group of Hill is probably the most complete, and we therefore adopt this name. It is possible that the lowest of Hill's Comanche group, viz., *Trinity beds*, may be uppermost Jurassic.

The Cretaceous series may be conveniently divided into Upper and Lower. The subdivisions of these are of course local. In Europe the Tertiary is nearly everywhere unconformable on the Cretaceous, showing a gap at this horizon; in America this gap is completely filled in the West by a transition group called the *Laramie*. The relation between the main divisions of the American Cretaceous on the interior

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* Wallace thinks that chalk is a coral mud formed in warm seas full of foraminiferal life (Island Life, p. 84).

† Favre, Archives des Sciences, vol. xxxvii, p. 118 *et seq.*

‡ Marcou had long ago (1853) discovered Neocomian in New Mexico, but the discovery was not recognized by American geologists.

This is partly a transition to Jurassic.

plains and Atlantic border, and of both with the European Cretaceous, is shown in the following table:

	AMERICAN.			EUROPEAN.
	WESTERN PLAINS.	ATLANTIC BORDER.	PACIFIC BORDER.	
LOWER TERTIARY.	Wahsatch and Puerco.	Eo-lignitic.	Tejon.	Thanet sands, Cernay beds.
Transition.	Laramie.	Wanting.		Wanting.
Upper Cretaceous.	Montana group.	Upper Cretaceous of N. J., Penn., and Miss.	Chico.	Chalk.
	Dakota group . .			Greensand.
Lower Cretaceous.	Comanche.	Raritan clays. Potomac upper part.	Shasta.	Neocomian.
Transition.	Trinity.	Potomac lowest part.	Aucella beds.	Wealden.
Upper Jurassic.	Baptanodon beds.	Wanting.		Purbeck.

Life-System: Plants.

Leaf-impressions are very abundant in the American Cretaceous, and the most cursory examination reveals at once a type of plants not seen in any lower rocks, viz., *Angiosperms*, both Dicotyls and Palms.

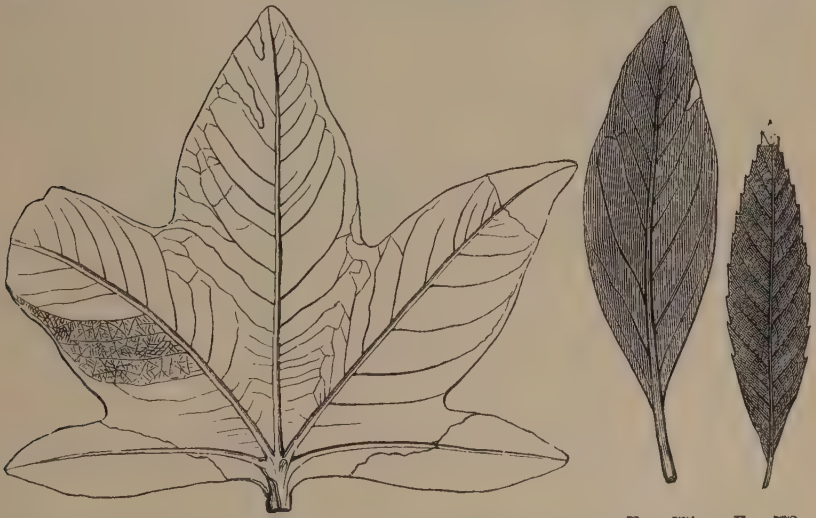

FIG. 770. FIG. 771. FIG. 772.

FIGS. 770–772.—CRETACEOUS PLANTS, DAKOTA GROUP (after Lesquereux): 770. Liquidambar integrifolium. 771. Laurus Nebrascensis. 772. Quercus primordialis. All reduced.

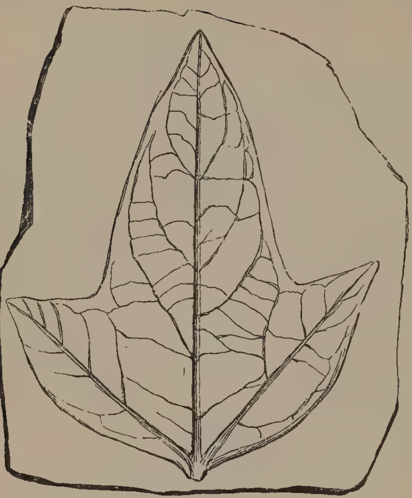

FIG. 773.

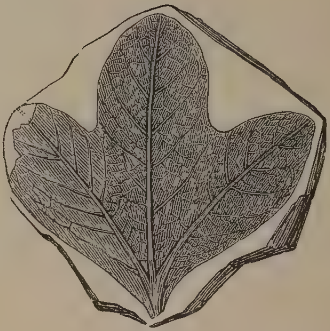

FIG. 774.

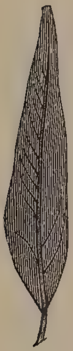

FIG. 775.

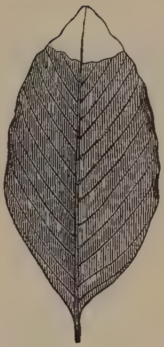

FIG. 776.

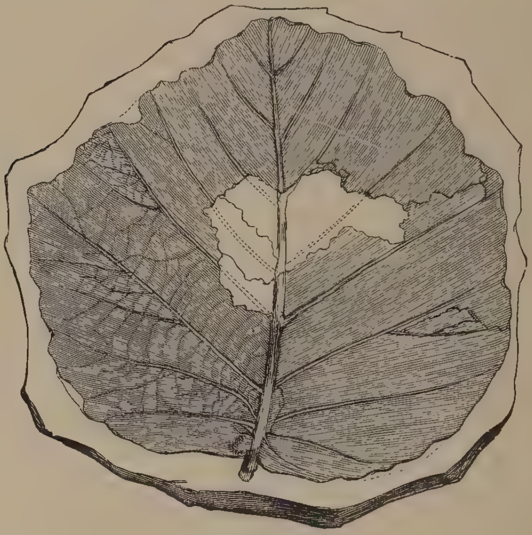

FIG. 777.

FIGS. 773–777.—CRETACEOUS PLANTS, DAKOTA GROUP (after Lesquereux): 773. Sassafras Mudgei. 774. Sassafras araliopsis. 775. Salix proteæfolia. 776. Fagus polyclada. 777. Protophyllum quadratum. All reduced.

We have said that the Sierra revolution at the end of the Jura-Trias produced important changes in America. A great break in the record occurs at this time in the region (the Plains) where these plants were first found. When the record commences again in the Dakota epoch we observe a very great difference in the subject-matter. The whole aspect of field and forest must have been different and much more modern. Nearly all the genera of our modern trees are present, e. g., *Oaks*, *Maples*, *Willows*, *Sassafras*, *Dogwood*, *Hickory*, *Beech*, *Poplar*, *Tulip-tree* (Liriodendron), *Walnut*, *Sycamore*, *Sweet-gum* (Liquidambar), *Laurel*, *Myrtle*, *Fig*, etc. Out of 460 species of plants found in the Dakota group, about 400 species are Dicotyls (Ward) and at least half of these belong to *living* genera (Lesquereux). And if we include the Laramie in the Cretaceous we may add 226 more species to the list, but these latter are quite different and more Tertiary in type. A few Palms have also been found in Vancouver's Island. So fully were these highest plants introduced here that although the Ceno*zoic* era commenced with the Tertiary, the Ceno*phytic* may be said to commence with the Cretaceous.*

It is a noteworthy fact that many of the most characteristic Cretaceous genera, and those most abundant and varied in species at that time, are now represented by only one or two species. For example, there are now only one or two species of Sassafras; two or three species of Plane-tree; one of Liriodendron; and two of Liquidambar. These are evidently the remnants of an extinct flora.

Origin of Dicotyls.—The appearance of these, the highest order of plants, in fully differentiated forms, seems sudden and without progenitors. But the obvious reason is, that where first discovered there was a great loss of record. The gap is now filled by the discovery of the Comanche group; and in the lowest part of this group on the Atlantic border (Potomac formation) have recently been found and described by Fontaine over 700 species of plants mostly of *Jurassic* types (Conifers, Cyads, and Ferns), but among them, and from the upper part of the formation, 76 species of Dicotyls. These earliest known Dicotyls (Figs. 778–782), though of very generalized character so far as genera and families are concerned, are yet well-differentiated, unmistakable Dicotyls. We must, therefore, look still lower, i. e., in the Jura, for their point of origin and for connecting links with other classes. These important discoveries leave us still in doubt as to the class of previously existing plants from which they may have sprung. It is very noteworthy, however, that certain curious leaves found in the Upper Jura and Lower Cretaceous, and heretofore referred to Ferns, are believed by Saporta to have been those of ancestors of the Dicotyls, and therefore called Pro-Angiosperms (Ward). It seems not improbable, therefore, that the Dicotyls have come from the Ferns.

But if the highest plants, the Dicotyls, are abundant, so are also the

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* As an explanation of the somewhat sudden appearance of Dicotyls it has been suggested by Woodworth that in Jura times the Dicotyls occupied isolated highlands, the richer plains being held by Mesozoic types by pre-emption right. Changing conditions gradually gave the advantage to the Dicotyls, which then came down to the plains, where their remains would be more likely to be preserved.

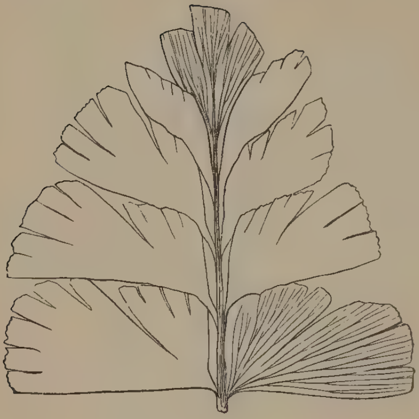

Fig. 778.

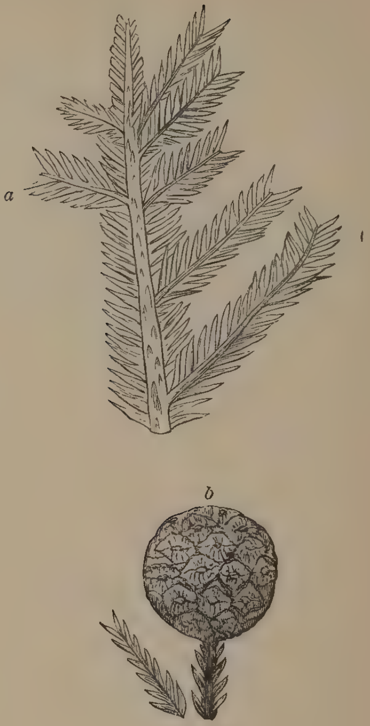

Fig. 779.

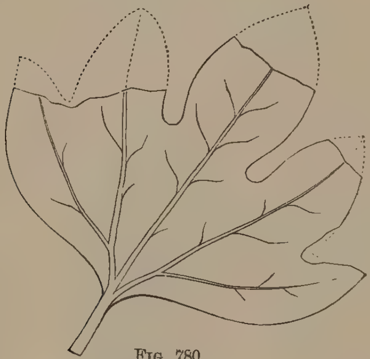

Fig. 780.

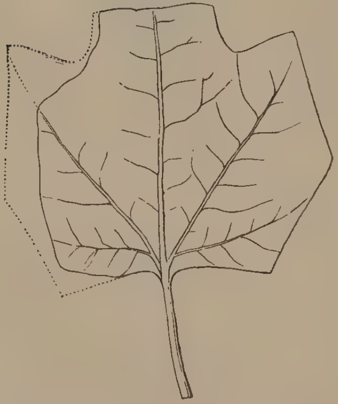

Fig. 781.

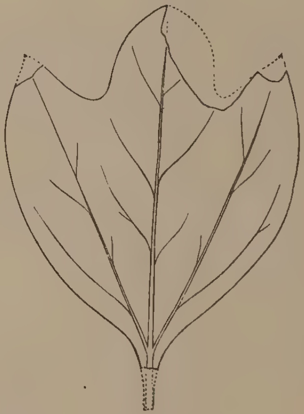

Fig. 782.

Figs. 778–782.—Plants of the Potomac Formation (after Fontaine)—*Conifers:* 778. Baieropsis foliosa. 779. Sequoia ambigua: *a*, Leafy branch; *b*, Cone. *Dicotyledons:* 780. Araliæphyllum obtusilobum, × ⅔. 781. Hederœphyllum angulatum, × ⅔. 782. Sassafras cretaceum, × ⅔.

lowest *Protophytes*, or uni-celled plants. Desmids and Coccospheres are abundant in the chalk of Europe.

Animals.

Protozoa. — As already stated, chalk is made up almost wholly of shells of Foraminiferæ (Rhizopods) and of certain uni-celled plants. According to Ehrenberg, a cubic inch often contains millions of microscopic organisms. More than 120 species of Foraminifers have been found in the English chalk alone. Some of these seem to be species *still living* in deep seas. These are all extremely minute, but some of larger size are found in the Cretaceous limestone of Texas. Those from the chalk have already been given (pp. 487 and 488).

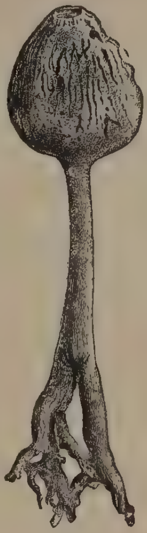
FIG. 783.

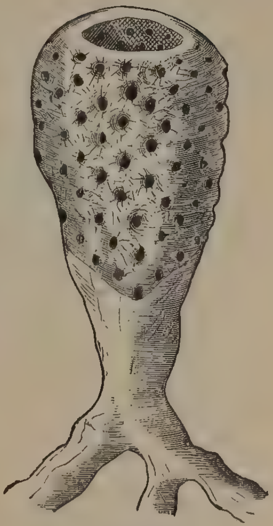
FIG. 784.

FIGS. 783, 784.—CRETACEOUS SPONGES: 783. Siphonia ficus. 784. Ventriculites simplex.

Sponges are extremely common in the chalk, as they are also in deep-sea bottoms of the present day. About one hundred have been found in the chalk.

Echinoderms.—The free Echinoderms are now for the first time in excess of the stemmed. The *Echinoids* are especially abundant and

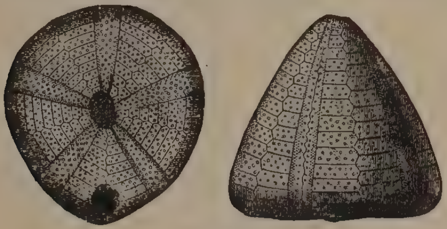
FIG. 785.

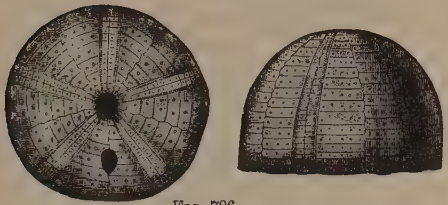
FIG. 786.

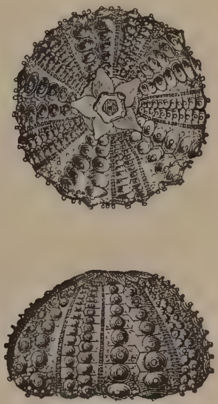
FIG. 787.

FIGS. 785-787.—ECHINOIDS OF THE CRETACEOUS OF EUROPE: 785. Galerites albogalerus. 786. Discoidea cylindrica. 787. Goniopygus major.

decidedly modern in type; and in the chalk some genera are identical with, and some species very similar to, those recently got from *deep-sea ooze.* The above are from the European Cretaceous.

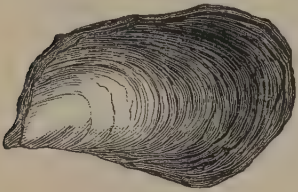

Fig. 788.

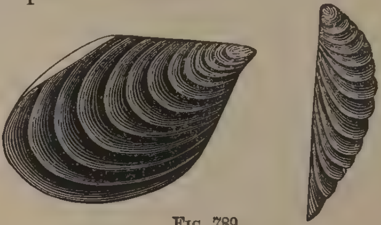

Fig. 789.

Figs. 788, 789.—Lamellibranchs: 788. Ostrea Idriænsis (after Gabb). 789. Inoceramus dimidius (after Meek).

Mollusks.—For the first time *Lamellibranchs* are fairly in excess of *Brachiopods.* Among the latter the modern family of *Terebratulæ* are especially conspicuous. Among the former the most noteworthy fact is the abundance of the Oyster family—*Ostrea*, *Gryphæa*, *Exogyra*, etc.; and the Avicula family, *Avicula*, *Inoceramus*, etc., some of which are of great size. We give some characteristic forms from the recently established Comanche group (Figs. 790–795).

Two very strange and characteristic groups of bivalve-shells occur here, and are very abundant, viz., the *Rudistes or Hippuritidæ* and the *Chamidæ.* In the former, one valve is small and often flat, while the other is enormously elongated like a cow's horn or even extended into fluted cylinders. In the latter one or both valves are elongated, and often coiled in the manner of a ram's horn. We give some figures

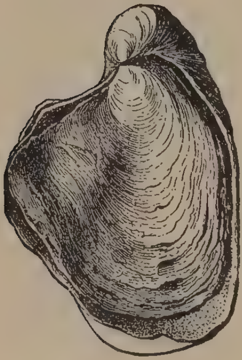

Fig. 790.

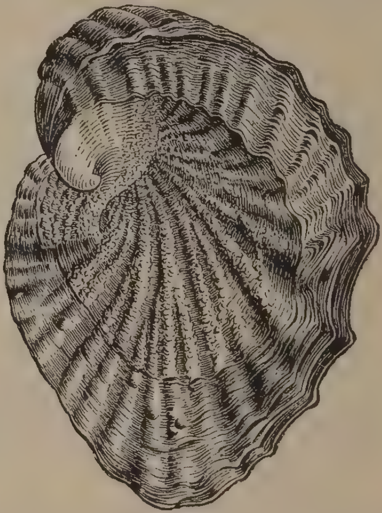

Fig. 791.

Figs. 790, 791.—Comanche Shells (after White): 790. Gryphæa Pitcheri. 791. Exogyra Texana.

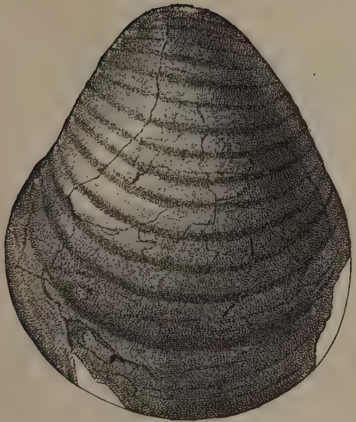

Fig. 792.

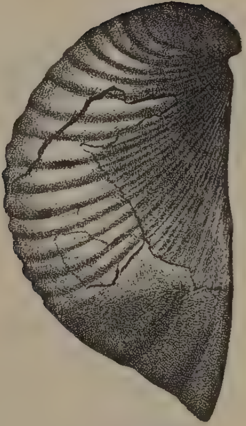

Fig. 793.

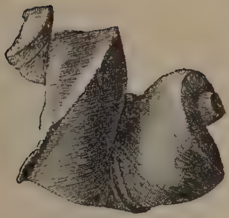

Fig. 794.

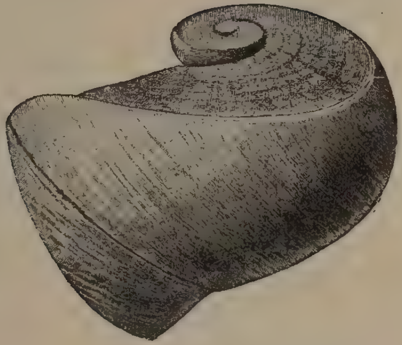

Fig. 795.

Figs. 792–795.—Comanche Shells (after White): 792. Aucella Erringtonii, Knoxville group, Cal. 793. Aucella, side view. 794. Requienia patagiata. 795. Requienia Texana.

of these strange forms (796–799) from foreign localities and some (794 and 795) from our *own country*.

Among *Gasteropods* (Figs. 796–799), the beaked or siphonated kinds are now for the first time abundant, as in the present seas.

Among *Cephalopods* the *Ammonites* and *Belemnites* still continue in great numbers and size, but they die out at the end of this period forever. In the Cretaceous of the Western Plains some Ammonites have been found over three feet in diameter (Dana). This family seemed to have reached its culmination just before its extinction. But what is still more remarkable is the introduction of many new genera of very strange and unexpected forms. These are sometimes *partly* uncoiled, as in *Scaphites* (boat), *Crioceras* (ram's-horn), *Toxoceras* (bow-horn), *Ancyloceras* (hook-horn), *Hamites* (hook); sometimes

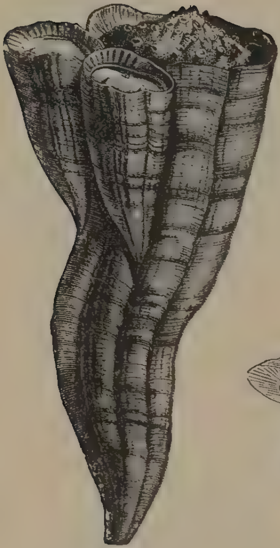

FIG. 796.

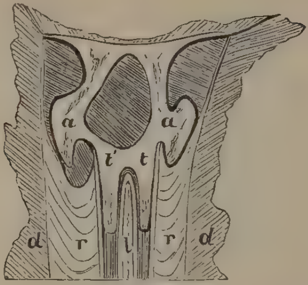

FIG. 797.

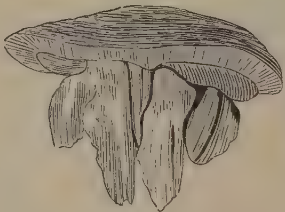

FIG. 798.

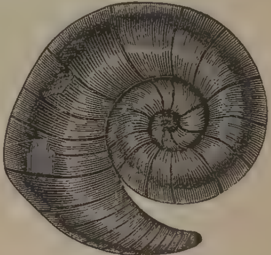

FIG. 799.

FIGS. 796–799.—796. Hippurites Toucasiana, a large individual with two small ones attached (after D'Orbigny). 797. Section of a Radiolites cylindriasus, showing structure. 798. Upper Valve of Radiolites mammelaris. 799. Caprina adversa (after Woodward).

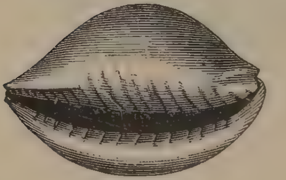

FIG. 800.

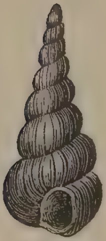

FIG. 802.

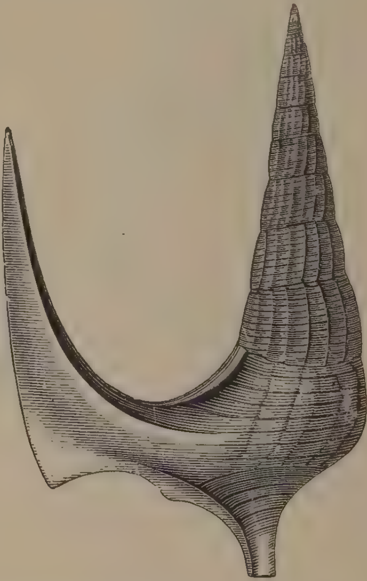

FIG. 801.

FIGS. 800–802.—CRETACEOUS GASTEROPODS: 800. Cypræa Matthewsonii (after Gabb). 801. Anchura falciformis (after Gabb). 802. Scalaria Sillimani (after Lesquereux).

completely uncoiled, as in *Baculites* (walking-stick); sometimes coiled spirally, like a Gasteropod, as in *Turrilites* and *Helioceras*. Belemnites (Fig. 810) also continue, though in diminishing numbers.

These strange forms have been likened by Agassiz to death-contortions of the Ammonite family; and such they really seem to be. They are degenerate forms of a declining type. From the point of view of evolution, it is natural to suppose that under the gradually-changing conditions which evidently prevailed in Cretaceous times, this vigorous Mesozoic type would be compelled to assume a great variety of forms, in the vain attempt to adapt itself to the new environment, and thus

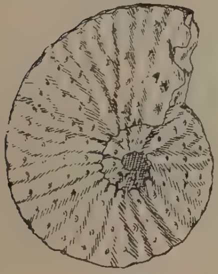
FIG. 803.

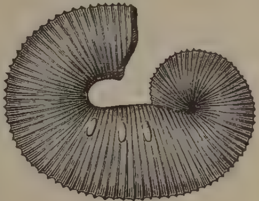
FIG. 804.

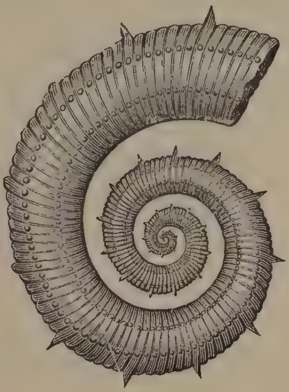
FIG. 805.

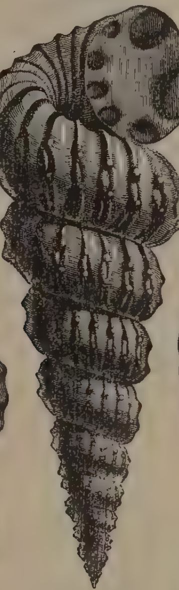
FIG. 809.

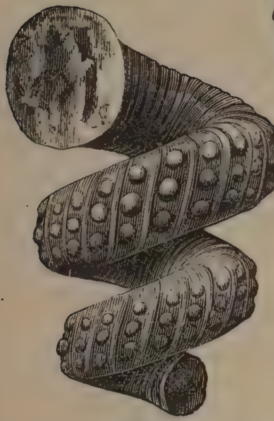
FIG. 806.

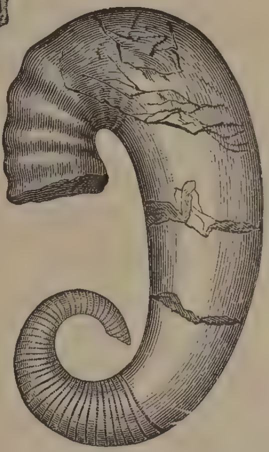
FIG. 807.

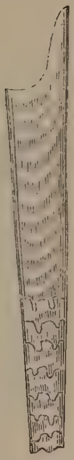
FIG. 808.

FIGS. 803-809.—CRETACEOUS CEPHALOPODS: 803. Ammonites Chicoensis (after Gabb). 804. Scaphites æqualis (after Pictet). 805. Crioceras, restored (after Pictet). 806. Helioceras Robertianus (after Pictet). 807. Ancyloceras percostatus, × ½ (after Gabb). 808. Baculites anceps, × ½ (after Woodward). 809. Turrilites catenatus (after D'Orbigny).

to escape its inevitable destiny. The curve of its rise, culmination, and decline, reached its highest point just before it was destroyed. The wave of its evolution crested and broke into strange forms at the moment of its dissolution.

Among *Crustaceans*, the Brachyurans, short-tailed Crustaceans (crabs), which were barely introduced in the Jurassic, are here represented by several genera.

Vertebrates—Fishes.—In the development of this class some decided steps in advance are here recorded. Placoids and Ganoids still continue, but *Teleosts*, or true typical modern fishes, are here introduced for the *first* time,* and in considerable numbers, and some of gigantic size. These earliest Teleosts were related to salmon, herring, perch, pike, etc. Beryx, a genus still found in open seas, is found in the Chalk of Europe and Upper Cretaceous of America. Among *Elasmobranchs*, too, although the Cestracionts and Hybodonts continue (the latter, however, passing out with the Cretaceous), the modern type, the true sharks or Squalodonts, having lancet-shaped teeth, are for the first time abundant. We give figures of Cestraciont (812) and Squalodont (811) teeth, and also a tooth, natural size, of a gigantic pike, eight feet long, from American Cretaceous, and a restoration of the same by Cope; also, two Teleosts from European Cretaceous.

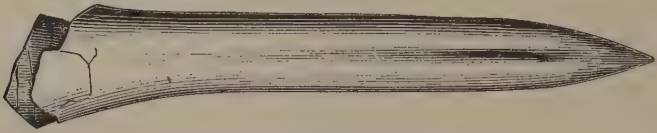

FIG. 810.—Belemnites impressus (after Gabb).

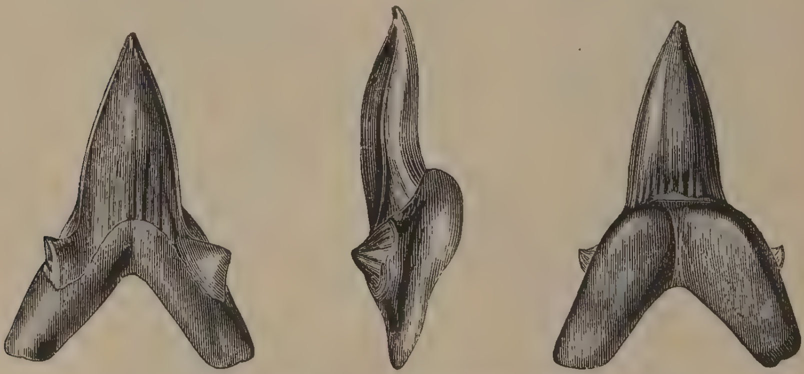

FIG. 811.—CRETACEOUS FISHES—*Elasmobranchs:* Otodus (after Leidy).

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* Some geologists make Teleosts appear in Jura; most, however, regard these supposed Teleosts as homocercal Ganoids.

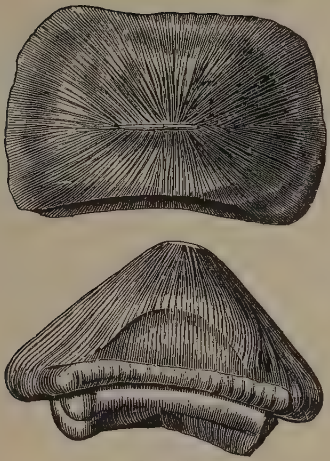

FIG. 812.

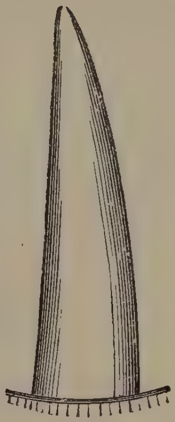

FIG. 813.

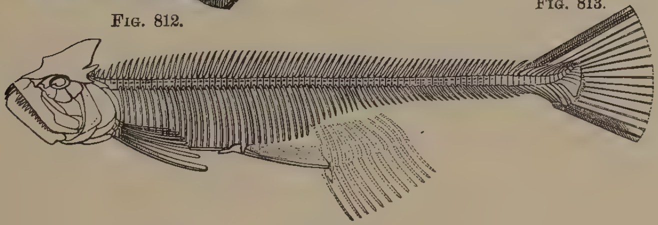

FIG. 814.

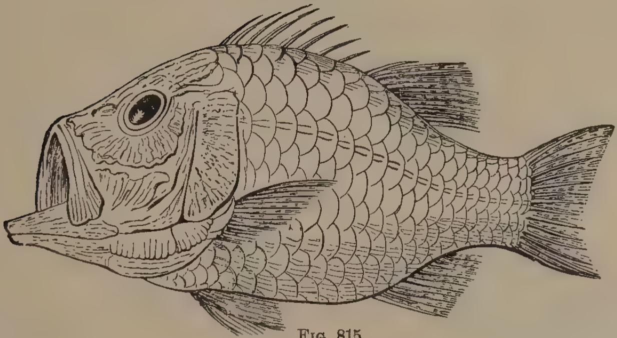

FIG. 815.

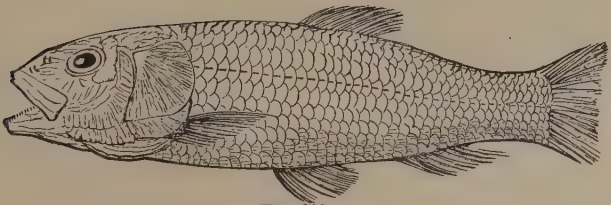

FIG. 816.

FIGS. 812–816.—CRETACEOUS FISHES—*Elasmobranchs*: 812. Ptychodus Mortoni (after Leidy). *Teleosts*: 813. Portheus molossus—Tooth, natural size (after Cope). 814. Portheus, restored, × $\frac{1}{28}$ (after Cope). 815. Beryx Lewesiensis. 816. Osmeroides Mantelli.

The *Hybodonts* were essentially a *Mesozoic* type; the Squalodonts are essentially Tertiary and modern. The two types coexist in the Cretaceous, the former passing out, the latter increasing, and finally displacing the former. The accompanying figure (Fig. 817) represents the succession, rise, culmination, and decline of the three families of sharks.

Cope gives ninety-seven species of North American Cretaceous fishes known in 1875. Of these, if we include the Chimera family, an aberrant type of sharks very common in the Cretaceous, *forty-five were Elasmobranchs.* The rest are mostly Teleosts, for the Ganoids are rapidly disappearing. In Europe twenty-five genera of Cycloids and fifteen of Ctenoids are found in the Cretaceous (Dana).

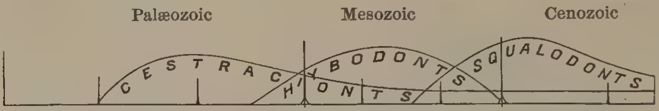

Fig. 817.—Diagram representing the Distribution in Time of Placoids.

Reptiles.—This class seems to have culminated about the end of the Jurassic or the beginning of the Cretaceous period. If their remains are more abundant in the Jurassic in Europe, they are far more abundant in the *uppermost Jurassic* (Atlantosaur beds) and in the Cretaceous in America. In fact, we had here in America during the Cretaceous an extraordinary abundance and variety of reptilian life, including all the principal orders already mentioned, viz., *Enaliosaurs*, *Dinosaurs*, *Pterosaurs*, and *Crocodilians*, and also a new type, introduced in the Cretaceous for the first time, the *Mosasaurs*, wholly marine in habits, but of long, slender, snake-like form, and attaining extraordinary length. Turtles were also found in large numbers and of great size. We can mention only a very few of the most remarkable of the Cretaceous reptiles.

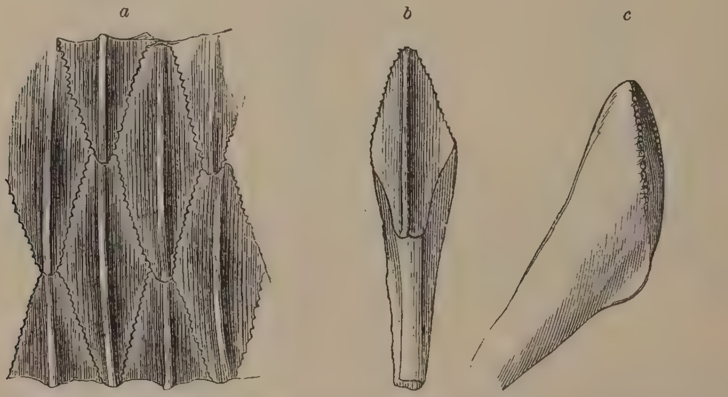

Fig. 818.—Teeth of Hadrosaurus (after Leidy): *a*, Pavement of Teeth; *b* and *c*, Tooth separated.

Among *Enaliosaurs* the *Ichthyosauridæ* are not found in America, but the *Plesiosauridæ* were abundant, and attained much greater size than in Europe. Leidy describes one, *Discosaur* (*Elasmosaur*, of Cope), which was fifty feet long, with a neck of sixty vertebræ and twenty-two feet long. Among *Dinosaurs the Hadrosaur* from New Jersey was twenty-eight feet long; and, judging from the huge size of its hind-legs and massiveness of its hips and small size of its fore-legs, it seems to have been able to stand and walk in the manner of birds. This animal was a vegetable feeder, with teeth somewhat like those of the Iguanodon, but set in several rows, so as to form a kind of tessellated pavement (Fig. 818). We give Fig. 819, a restoration by Marsh, of an allied form from the European Cretaceous. From the New Jersey Cretaceous have been found also the *Dryptosaurus* (*Lælaps*), similar to the Megalosaur and twenty-four feet long, and the *Ornithotarsus* (bird-shank), thirty-five feet long, stood twelve to fifteen feet high when walking on their hind-legs. Among *Pterosaurs*, Marsh has found in the Western Cretaceous the remains of at least seven species, two of which were twenty to twenty-five feet in alar extent, and another eighteen feet.

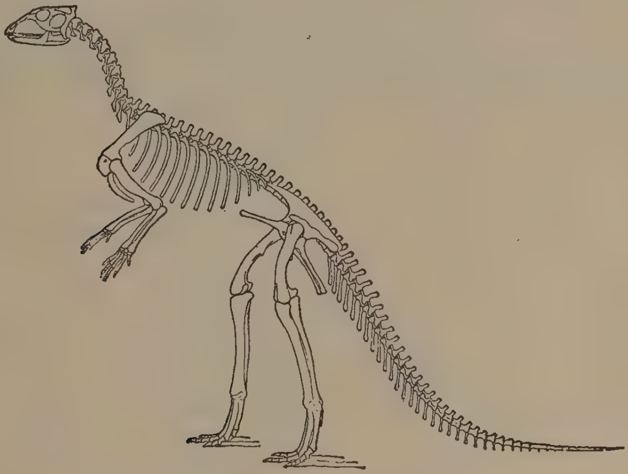

FIG. 819.—Hypsilophodon ($\frac{1}{18}$) (restored by Marsh).

The American Pterosaurs differ from all other known Pterosaurs in the fact, recently brought to light by Marsh, that their jaws were entirely *toothless*, and probably *sheathed with horn*, as in birds. They have therefore been placed by Marsh in a distinct order, *Pteranodontia*, from the type genus *Pteranodon* (winged toothless). Probably all the American Pterosaurs belong to this order. One of them, *P.*

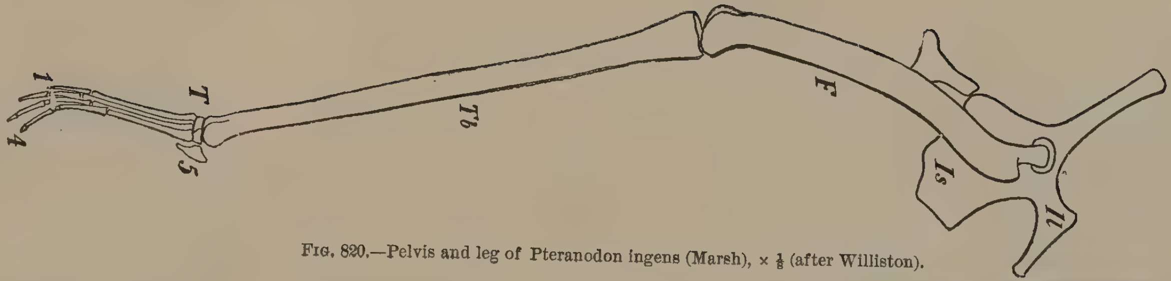

FIG. 820.—Pelvis and leg of Pteranodon ingens (Marsh), × $\frac{1}{8}$ (after Williston).

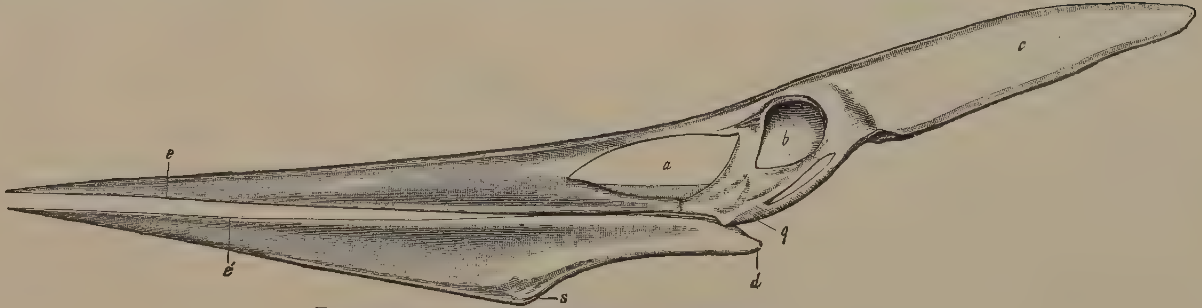

FIG. 821.—Skull of Pteranodon longiceps, × $\frac{1}{8}$ (after Marsh).

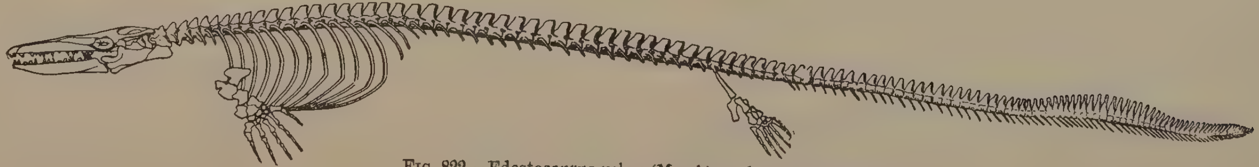

FIG. 822.—Edestosaurus velox (Marsh), × $\frac{1}{21}$ (after Williston).

igens, had toothless jaws four feet long, and an expanse of wing of more than twenty-two feet.

Among the many *Chelonians* (turtles) found in the Cretaceous of the Western Plains, of the Rocky Mountain region, and of New Jersey, one, the *Atlantochelys gigas*, had a length of nearly thirteen feet, and a breadth across the extended flippers of fifteen feet (Cope). The structure of this huge turtle was singularly *embryonic*. The flattened ribs, which by their coalescence make the greater part of a shell of a turtle, were in this species, as in the embryo of modern turtles, *not yet coalesced*.

But the most remarkable and characteristic reptiles found in the Cretaceous are the *Mosasaurs* (*Pythonomorpha* of Cope). The first specimen of the order was found in Europe, on the river Meuse, and

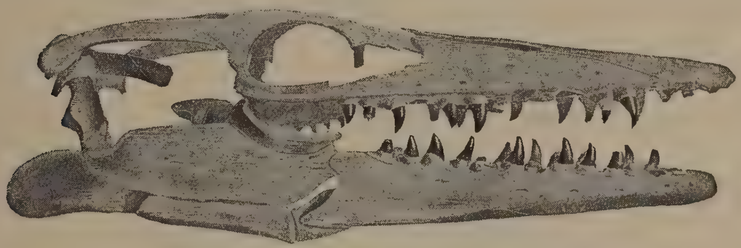

FIG. 823.—Head of a Tylosaurus proriger (after Merriam).

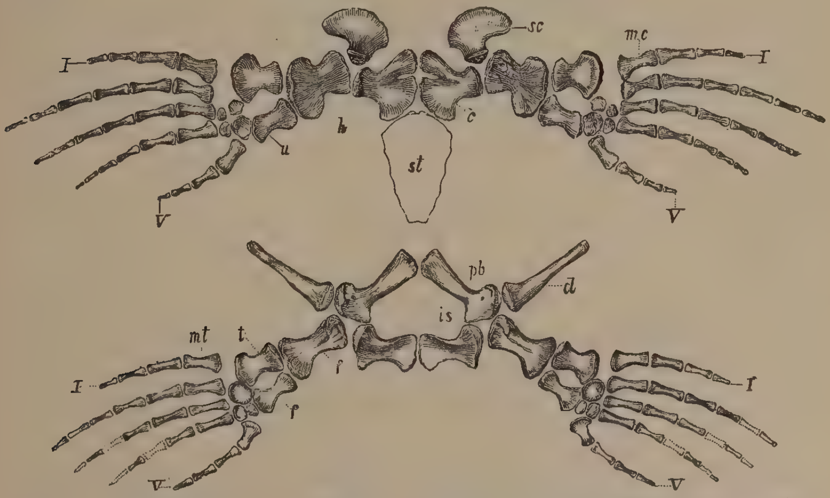

FIG. 824.—*A*. Scapular arch and fore-limbs of Lestosaurus simus (after Marsh), seen from below, one sixteenth natural size, with outline of sternum from Edestosaurus. *B*. Pelvic arch and hind-limbs of Lestosaurus simus, seen from below. One twelfth natural size. *il*, ilium; *pb*, pubis; *is*, ischium; *f*, femur; *t*. tibia; *f'*, fibula; *mt*, metatarsal. The paddles are represented as horizontal, and the bones of the arches are somewhat displaced to bring them into the same plane.

hence the name Mosasaurs; but they seem to have been far more abundant in America. At least fifty species (Cope) have been found in the Cretaceous of New Jersey, the Gulf States, and Kansas. Of these, the *Mosasaurus princeps* was sixty to seventy feet long, and *Tylosaurus* (*Liodon*) *dyspelor* probably "attained a length equal to the longest whale" (Cope). These reptiles seemed to have united the long, slender form of a snake, and the short, strong, well-fingered paddles of a whale, with the essential characters of a lizard. Another snake-like character possessed by this order was rows of teeth on the pterygoid bones, in addition to those in the jaws; and a peculiar joint in the lower jaws, by means of which, when aided by the recurved teeth, the jaws could act separately like arms, in dragging down their throats prey which was too large to swallow directly (Fig. 825).

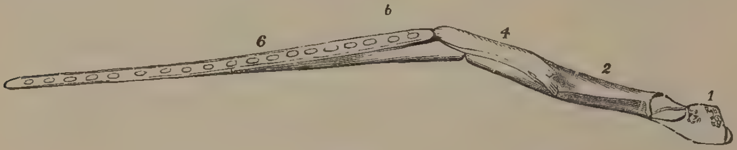

FIG. 825.—Jaw of a Edestosaurus, × ½ (after Cope).

The number of species are yearly increasing by new discoveries. The remains of at least fourteen hundred individuals of Mosasauroids alone are now gathered in Marsh's collection.

According to Cope, 147 species of reptiles have been described from the Cretaceous of North America, of which fifty are Mosasaurs, forty-eight Testudinata (turtles and tortoises), eighteen Dinosaurs, fourteen Crocodilians, thirteen Sauropterygia (Plesiosaur-like), and four Pterosaurs. At least three more Pterosaurs have been found, making the whole number seven (Marsh).

In Europe, Iguanodons, Teleosaurs, Ichthyosaurs, Plesiosaurs, and Pterosaurs still continue in the Cretaceous, some of the last being twenty-five feet in expanse of wing; and also Mosasaurs were introduced.

Birds.—The history of the discovery of the earlier fossil birds is instructive. Until 1858, with the exception of the doubtful tracks in the Connecticut River sandstone, no birds had been found lower than the Tertiary. In that year the bones of a bird, probably related to the gull, were found in the upper greensand of England. In 1862 the wonderful reptilian bird *Archæopteryx macroura*, already described (p. 462), was found in the Solenhofen limestone of Germany (Upper Jurassic). In 1870, and subsequently, Marsh discovered in the Cretaceous of New Jersey and Kansas about twenty species of birds. Those from New Jersey were from the Uppermost Cretaceous (Foxhill group), and are probably true birds—waders and swimmers—though not of the higher orders. Those from Kansas are from a lower horizon (Colorada group), and are all wonderful, toothed birds, entirely different from any existing order. With the exception of the Archæopteryx, these are the most extraordinary birds yet discovered. Some of them, belonging to the two genera *Ichthyornis* and *Apatornis*, may have been, partly at least, *without* the horny *beak* so characteristic of existing birds, but instead had *thin*, *long*, *slender jaws*, *furnished with many sharp*, *conical teeth*, *set in sockets*, twenty on each side below, and somewhat fewer above (Fig. 826). The edentulous anterior part was probably covered with horn. Their vertebræ were amphicœlous or biconcave, as in fishes and many extinct reptiles, but in no modern bird

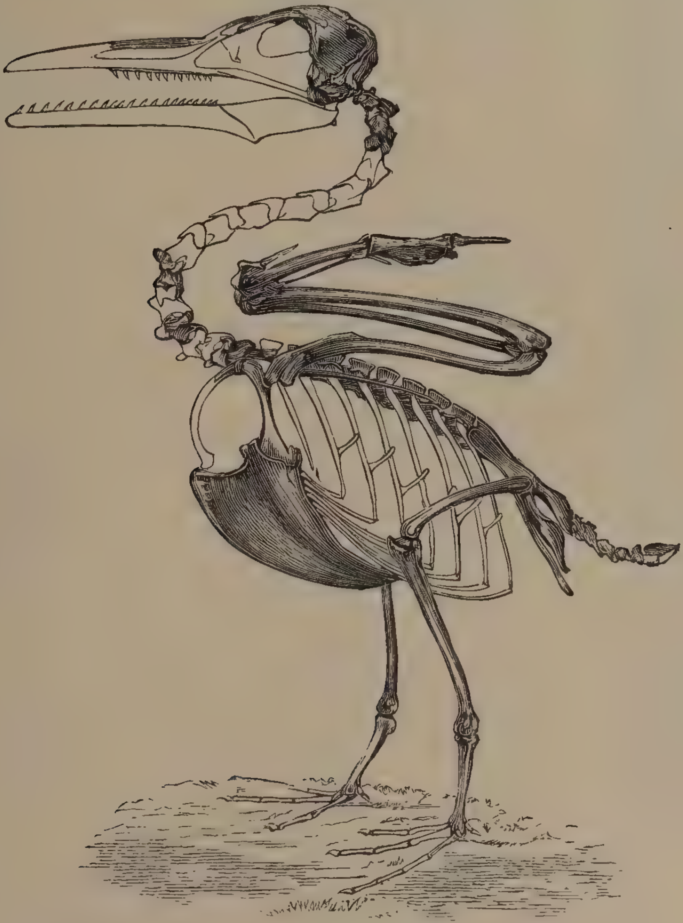

Fig. 826.—Restoration of Ichthyornis victor (after Marsh). One half natural size.

(Fig. 828). Like modern birds, however, they had a keel on the breast-bone for the attachment of the powerful muscles of flight. The tail also is worthy of attention, being not like that of the Jurassic Archæopteryx, but much shorter and not so reptilian (Marsh). These birds were about the size of a pigeon, and were evidently powerful fliers. Fig. 826 is a restoration by Marsh of one of this type. The other toothed birds had similar jaws, but their teeth were set in grooves

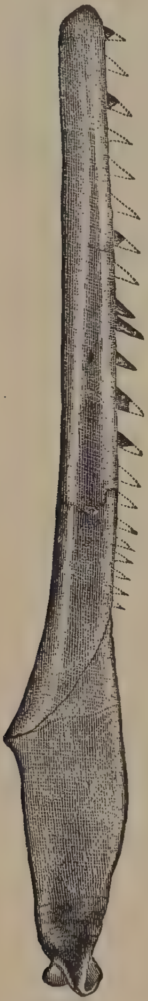

FIG. 827.

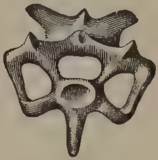

FIG. 828.

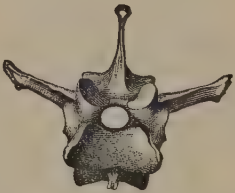

FIG. 830.

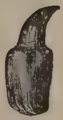

FIG. 831.

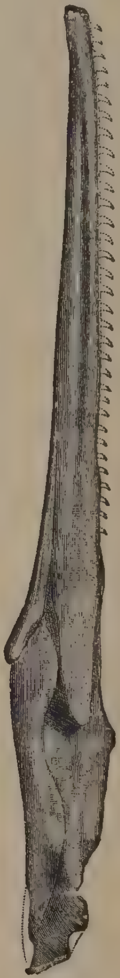

FIG. 829.

FIGS. 827-831.—ODONTORNITHES (after Marsh): 827. Lower Jaw of Ichthyornis dispar, × 2. 828. Cervical Vertebra of same, × 2. 829. Lower Jaw of Hesperornis regalis, × ½. 830. Dorsal Vertebra, × ½. 831. Tooth of same, × 2.

instead of distinct sockets (Fig. 829), and they differed also in having no keel and in having ordinary bird-vertebræ (Fig. 830). These were evidently divers, and *incapable of flight.* Two of them—*Hesperornis regalis* and *Lestornis crassipes*—were of gigantic size, being from five to six feet from snout to toe. In the accompanying figure (Fig. 832) we give a restoration by Marsh of one of these remarkable birds. The anterior toothless part of the beak was probably horny. In these birds, therefore, we have the most extraordinary combination of bird characters with reptilian and fish characters. So extraordinary and exceptional is this combination of characters, that Marsh believes he is justified in placing them not only in new orders, but even in a new sub-class. According to this authority, the class of Birds may be divided into two sub-classes, viz., *Ornithes*, or true birds, and *Odontornithes*, or *toothed* birds. And the new sub-class Odontornithes into three orders, viz.: (1) *Saururæ* (*reptile-tailed*), represented by the Archæopteryx, (2) *Odontolcæ* (teeth in grooves), represented by the Hesperornis, and (3) *Odontotormæ* (teeth in sockets), represented by the Ichthyornis. Yet exceptional as these characters may seem, they are just what the law of evolution would

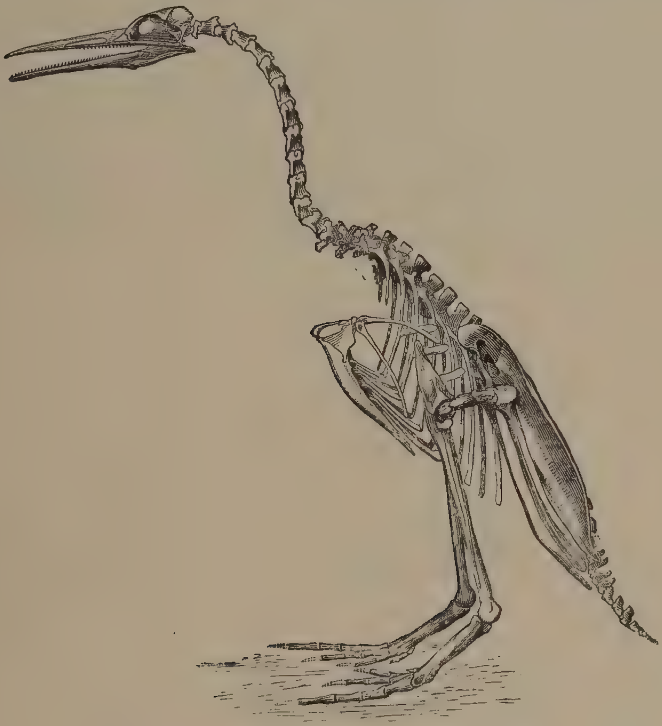

FIG. 832.—Hesperornis regalis, × $\frac{1}{10}$ (restored by Marsh).

lead us to expect in the earliest birds. As already stated (p. 473) this branch had not yet been fairly separated from the reptilian stem. It is a noteworthy fact that these toothed birds lived at the same time and in the same localities with the toothless Pterosaurs mentioned on page 503.

It is well to observe that in the earliest representatives of each class the brain is relatively very small. This is true of reptiles, birds, and mammals, as Marsh has shown. We give below figures taken from Marsh, showing the relative size of the brain in living and Cretaceous birds.

Mammals.—It is a most remarkable fact that although Marsupial mammals have been found in the Jurassic, and probably existed in considerable numbers then, yet, except in the Laramie which may be regarded as a transition to the Tertiary, not one has been found in the Cretaceous. We know they existed at that time, for they are found in the Laramie of America and in the Tertiary of both Europe and America, and *still* exist in Australia and elsewhere; and it is a well-established law in Paleontology that if a type becomes extinct *it never reappears:* Evolution never goes backward: Nature never repeats herself. It is probable, therefore, that during the Cretaceous the Marsupials which doubtless existed had been driven to some other portion of the earth, where we shall yet find their remains when our knowledge of the geology of the globe is more complete; and in them we shall also probably find the transitions to, or earliest progenitors of, the True Mammals of the Tertiary.*

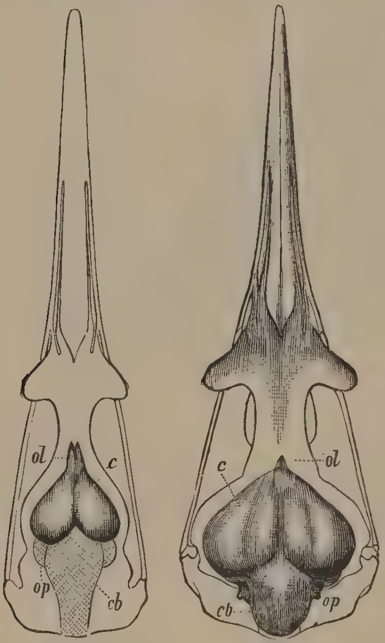

FIG. 833. FIG. 834.

FIGS. 833, 834.—833. Outline of the skull and brain-cavity of Ichthyornis victor (after Marsh), seen from above. Five sixths natural size. 834. Outline of the skull and brain-cavity of Sterna cantiaca (after Gmelin), same view. Natural size. *ol*, olfactory lobes; *c*, cerebral hemispheres; *op*, optic lobes; *cb*, cerebellum.

Continuity of the Chalk.

It is probable that the deep Atlantic Ocean bottom, where chalk is now forming, is continuous with the chalk of England and Central Europe. In other words, in Cretaceous times a deep sea ran from the mid-Atlantic far into what is now Central Europe, and in the whole of this deep sea chalk was then formed. At the end of the Cretaceous period the eastern part was raised and formed a portion of Europe, while the rest remained as deep-sea bottom, and continued to make chalk until now. Thus there is no doubt that in the deep Atlantic, off the coast of Europe, there has been *an unbroken continuity of chalk-making from the Cretaceous times until now.* But we have seen (p. 495) that many of the living deep-sea species are identical with, and nearly all extremely similar to, those found in the chalk of Cretaceous times. Thus there has been not only a continuity of chalk-formation, but also to some extent of the *chalk-fauna*, to the present time.

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* Or possibly driven not to another country, but to uplands and mountains, which are unfavorable for preservation of their remains (Woodworth).

These facts were certainly unexpected, but, so far from shaking the foundations of geological science, as some have imagined, they are in perfect accordance with the fundamental principles of geological succession properly understood; as we now proceed to show:

1. The facts of identity have been exaggerated. Many of the *Foraminifera only are identical.* Among Echinoderms the identity is generic, not specific. 2. In comparing higher with lower species, we find that the lower species are widely distributed both in space (geographically) and in time (geologically), and that the continuance or range in time becomes less and less in proportion as we rise in the scale. Fig. 835 is constructed to illustrate this point; we see that living species of mammals extend back only a little way into the Quaternary, living species of mollusks back to the beginning of the Tertiary, while living species of Foraminifera, as we might expect, extend back into the Cretaceous. 3. There is a necessary relation between fauna and external conditions. Changes in the latter determine corresponding changes in the former. Now, deep-sea conditions are evidently far less subject to change—far more continuous—than shallow-water and land conditions. For this reason, we should expect deep-sea faunas to change very slowly. 4. But this can not affect the geological chronology, *because this chronology rests almost wholly on the remains of shallow-water and land animals.* Chalk is the only profound sea-bottom formation certainly known. It is, therefore, wholly exceptional.

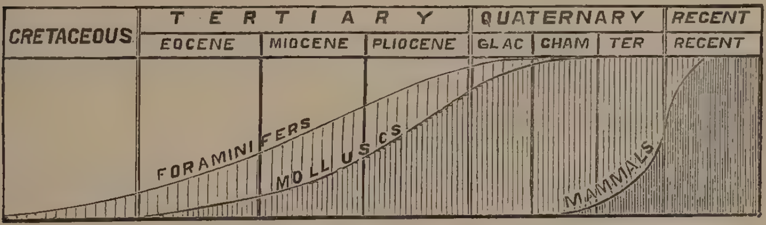

FIG. 835.—Diagram illustrating the Relative Duration of Lower and Higher Species.

5. The reason it is exceptional is that, as a broad general fact, the present continents have been, through all geological times, steadily heaved upward out of the ocean, growing larger and higher; and, therefore, the successive additions have been nearly always *shallow marginal bottoms* and *shallow interior seas.* That the exception should occur in Europe more than in America, too, is in keeping with the general character of the development of the European as contrasted with the American Continent. Chalk is also found in Texas, Kansas, and northward; but here also was a deep interior sea, an extension of the Mexican Gulf. 6. Conversely, the fact that chalk is so exceptional is proof of the development of continents as indicated under the last head—proof that, as a general fact, the great inequalities of the earth's crust, which constitute land-surfaces and sea-bottoms, have remained substantially unchanged *in position* from the first, while steadily increasing in vertical dimensions.

General Observations on the Mesozoic.

The Mesozoic, and especially the Jurassic, is characterized by the culmination of two great classes of animal, viz., *Cephalopod Mollusks* and *Reptiles*, and one of plants, the *Cycads.* This is shown in the diagram on page 294. The culmination of reptiles is, of course, its most distinguishing characteristic. That it was pre-eminently an age of Reptiles, may be shown by a comparison of its reptilian fauna with that of the present day. There are *now*, on the *whole* face of the earth, only six or seven large reptiles over fifteen feet long—two or three in India, one in Africa, three in America—and none over twenty-five feet long. In the *Wealden* and Lower Cretaceous of *Great Britain alone* there were sixteen great Dinosaurs, several twenty to fifty feet long, ten to twelve Crocodilians and Enaliosaurs ten to fifty feet long, besides *Pterodactyls*, turtles, etc. (Dana). Again, in the *Cretaceous of the United States alone* the fullness of reptilian life was even greater; for 150 species of reptiles have been found, most of them of gigantic size. Among these were fifty species of Mosasaurs, some seventy to eighty feet long; many huge Dinosaurs, twenty to fifty feet long; besides Enaliosaurs, Pterosaurs, and gigantic turtles (Cope). These are *preserved!* But the known fossil fauna of any period is but a fragment of the actual fauna of that period. Not only did reptiles greatly predominate, but the age seemed to impress its reptilian character on all other higher animals existing at that time. The birds were reptilian birds, the mammals were reptilian mammals. All animals as yet were *oviparous* (birds, reptiles, and monotremes) or *semi-oviparous* (marsupials).

That the *climate* was then warm and uniform is sufficiently attested by the character of the fauna and flora. All great reptiles and all Cycads and Tree-ferns are found now only in tropical or sub-tropical regions. This tropical fauna and flora were substantially similar in all latitudes in which the strata have been found—even as far north as Spitzbergen (Nordenskiöld) * and to Exmouth Island, 77° (Dana). During the *latter* portion of the Cretaceous period, as indicated by the abundance of *deciduous* Dicotyls, the climate of North America had become cooler, being about 8° or 10° warmer than now. Temperature zones seem to begin to appear first in the Cretaceous.

Disturbance which closed the Mesozoic—Rocky Mountain Revolution.—The disturbance which in America closed the Cretaceous period and the Mesozoic era was an arching of the earth's crust over the whole Plains and Plateau region, by which the great interior Cretaceous sea, which previously divided America into two continents, was abolished, and the continent became one. At the same time the Wahsatch and Uintah Mountains were principally formed, and the eastern Rocky Mountain range greatly elevated. As the Palæozoic closed with the Appalachian revolution, so the Mesozoic closed with what may be called *the Rocky Mountain revolution.* The disturbance, as usual with those which close an era, was probably to some extent *oscillatory*—i. e., the continent was probably higher and cooler during the latter part of the Cretaceous than during the subsequent Eocene. The change of physical geography was enormous, and the change of climate was doubtless correspondingly great. We ought to be prepared, therefore, to find, with the opening of the next era, a very great change in the organisms.

Laramie, or Transition Epoch.

In the schedule on page 491, we have indicated a transition epoch called the *Laramie.* There has been much controversy about the true position of these strata. Some have put them in the Tertiary, some in the Cretaceous, and some have regarded them as completely transitional between the two; while still others would solve the difficulty by assigning the lower part to the Cretaceous and the upper part to the Tertiary. Stratigraphically the Laramie is continuous with the Cretaceous below, and in some places also with the Tertiary above; so that the Cretaceous of the West in some places gradates through the Laramie into the Tertiary without break. This is especially true in California, where the Upper Cretaceous seems to gradate completely and without break through the Tejon group into the Tertiary. The difficulty of drawing the line of separation on paleontological grounds is equally great. The plants are decidedly Tertiary in general aspect, but the animals, especially the land-animals, are as decidedly Cretaceous; the shells meanwhile passing from the marine through brackish-water into fresh-water forms. Cretaceous Dinosaurs still linger, but Tertiary types of Plants have already taken possession. Many palæobotanists claim it for Tertiary. Nearly all palæozoölogists put it in the Cretaceous. There is little doubt that it is really transitional, although probably more closely allied with the Cretaceous.

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* Geological Magazine, November, 1875.

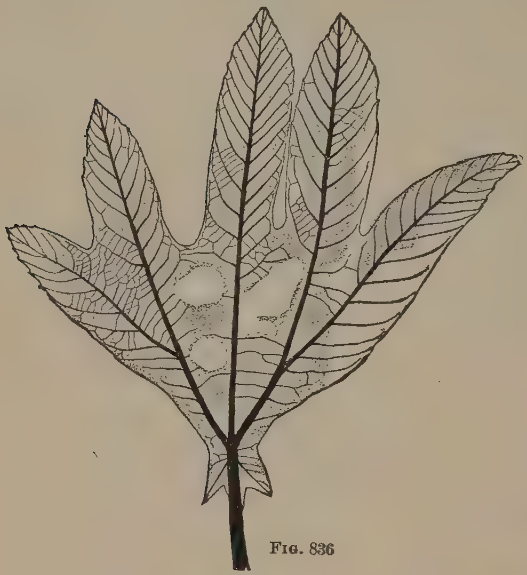

Fig. 836

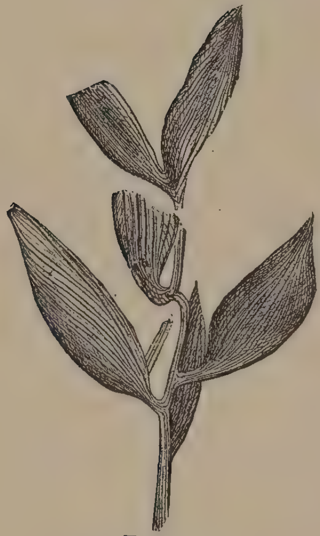

Fig. 837.

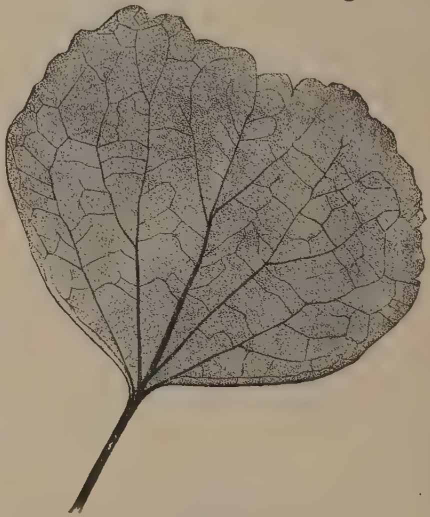

Fig. 838.

Figs. 836–838.—836. Aralia digitata. 837. Leguminositis arachioides. 838. Populus cuneata.

The explanation of these facts is obvious: We have seen that at the end of the Cretaceous the great interior Cretaceous sea was abolished by elevation, and its place (as we shall see hereafter) was partly occupied by great fresh-water lakes. Now, this change took place somewhat *gradually*, the oceanic condition passing into the lake-condition *through an intermediate* brackish-water condition of isolated seas, the sedimentation going on all the time. While oceanic conditions prevailed, the deposits are undoubtedly Cretaceous. When lake-conditions are fairly established, they are undoubtedly Tertiary; the intermediate brackish-water deposits are the Laramie. But, as the change was gradual and the sedimentation continuous, of course the strata were in places conformable throughout. Thus, then, the Cretaceous was before, the Tertiary after, and the Laramie during, the Rocky Mountain revolution.

In regard to the Life-system the explanation is similar. The abolition of the interior Cretaceous sea and the unification of the continent was a great event, and produced very great change in physical conditions. There was, therefore, a corresponding change in the Life-system. But this was also gradual. The Cretaceous Dinosaurs still lingered, ready to disappear; but as new land appeared it was taken possession of by new types of Plants, probably migrated from the north: and thus Cretaceous land-animals and Tertiary land-plants existed side by side. Meanwhile the marine shells by changing conditions were most of them destroyed, but some changed through brackish-water forms into fresh-water forms of the Tertiary. Some of the steps of this change of molluscan types have been traced (White).

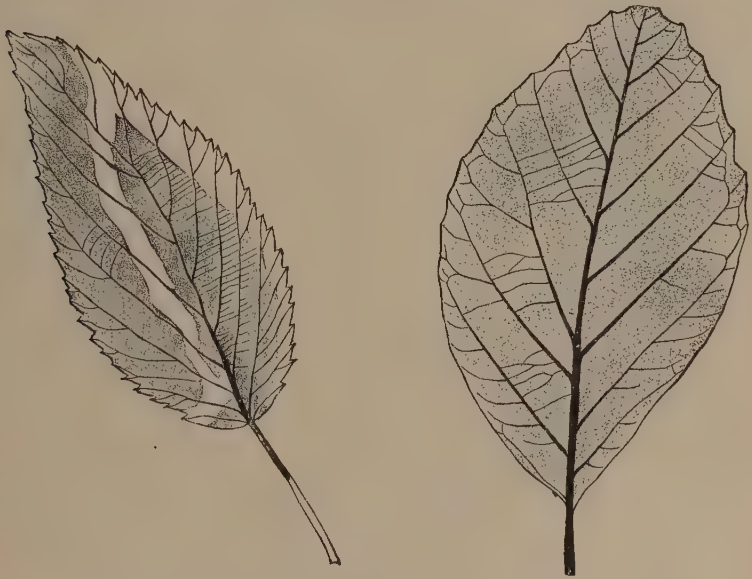

Fig. 839. Fig. 840.

Figs. 839, 840.—839. Viburnum Newberrianum. 840. Alnus Grewiopsis.

Such transition strata are of especial interest, and deserve separate treatment in order to emphasize their transitional character.

Area.—From what is said above it is evident that the Laramie exists over very wide areas in the region of the interior Cretaceous sea, but it is largely covered by Tertiary lake deposits. It is, however, exposed along the eastern base of the Colorado mountains, from Mexico northward far into British America; also in the Laramie plains, where it is traversed by the Union Pacific Railroad. This is the typical locality from which it takes its name. On the Pacific coast, a part at least of the Tejon group, and also the principal coal-fields of California, Washington, and British Columbia, probably belong to this horizon. In the typical locality, on the Laramie plains, the strata are several thousand feet thick. It represents, therefore, a long period of time.

Life-System—Plants.—The vegetation was very abundant, and the plants had already assumed a Tertiary aspect. About 323 species of plants are known, of which 226 species are Dicotyls. We give a few illustrations of these from Ward (Figs. 836–840).

Coal.—As the Palæozoic, so also the Mesozoic closes with a great coal period (Dana). Conditions seem to have been again favorable for the accumulation and preservation of the abundant vegetation. Next to the Carboniferous, by far the largest coal-fields of the United States and of British America belong to the Cretaceous, and especially to this horizon. The most important of these Cretaceous coals are the following: 1. A large field covering the greater portion of Western Kansas and Eastern Colorado. 2. Another valuable field in New Mexico, of almost equal size. 3. Still another of greater size in Dakota, and extending northward far into British America. These are, all of them, on the *Plains*. 4. On the *Plateau* a valuable field covers nearly the whole of the Laramie plains in Wyoming, and stretching to the border of Utah. The area of these coal-fields of the Plains and Plateau region is not known, but must be enormous. Some of the fields are also of extraordinary richness, the seams being often fifteen to twenty feet thick. They almost rival the great fields of the Carboniferous, already described. On the *Pacific border* there are several fields, which probably belong to the same horizon, viz.: 1. Monte Diablo and Corral Hollow coal-field in California. 2. Seattle, Carbon Hill, and Bellingham Bay coals of Washington. 3. Nanaimo or Wellington coals of Vancouver's Island, British Columbia. This last, however, probably belongs to the Cretaceous proper, not to the Laramie.

Cretaceous coal occurs also in other countries in large quantities, especially in Northern France and in China.

It is usual to call all these later coals *Lignites*, and to imagine that they are very inferior; but much of the Laramie coal is of good quality, and hardly distinguishable in appearance from coal of the Carboniferous age.

Animals.—We give a few characteristic *shells*, taken from White (Figs. 841–844); but the greatest interest centers in the *Dinosaurs*, and especially the recently discovered *mammals* of this epoch. As we have already said, the Dinosaurs still continued to linger, but under rapidly changing conditions, and ready to disappear. And here, again, as in the case of Ammonites (p. 499), we observe that the last survivors take on strange and grotesque forms. In this class, also, as in the case of Ammonites, the wave of evolution crested and broke into strange forms at the moment of its dissolution. The most remarkable of all Dinosaurs were the different species of *Triceratops* (three-horned face, Fig. 845). This genus was characterized by the possession of two enormous horns, three feet long and ten inches in diameter on the frontal bones, and one of smaller size on the nose; and by a large occipital crest projecting backward and outward and curving downward,

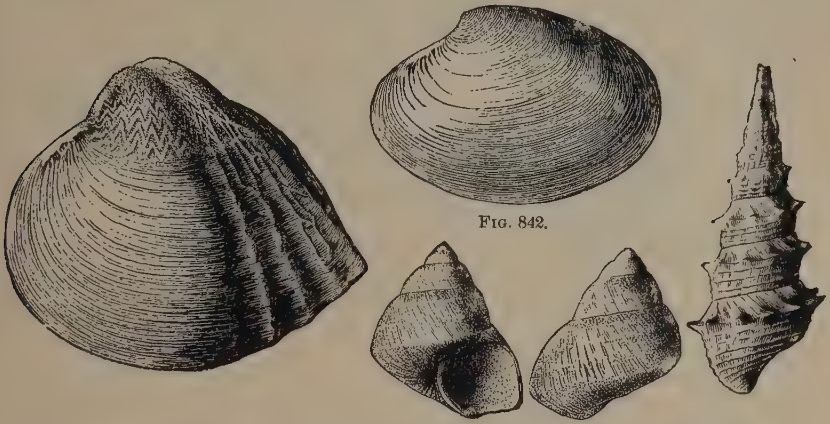

Fig. 842.

Fig. 841. Fig. 844. Fig. 843.

Figs. 841–844.—Laramie Shells (after White): 841. Unio Holmesianus. 842. Corbicula fracta. 843. Melania Wyomingensis. 844. Viviparus trochiformis.

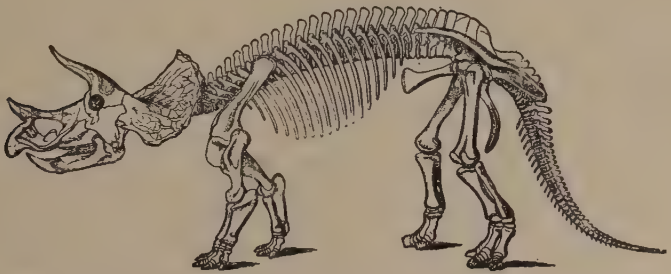

Fig. 845.—Triceratops prorsus (after Marsh), $\times \frac{1}{80}$, Cretaceous, Wyoming.

and fringed around with short horns somewhat in the manner of the horned lizard (*Phrynosoma*). The end of the snout also was toothless, and covered with horn forming a beak. A head of one of these has been found more than six feet long and four feet wide, and another over eight feet long. Of all reptiles this was probably the most beast-like in its tread.

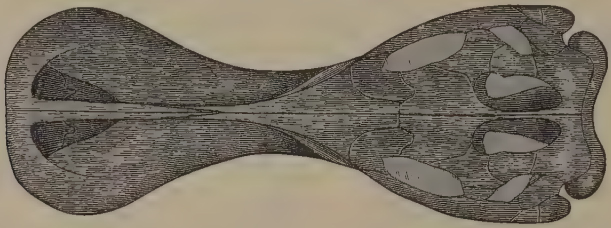

FIG. 846.—Diclonius mirabilis, × $\frac{1}{14}$ (after Cope).

Another strange Dinosaur of this time was the *Diclonius mirabilis* of Leidy, a head of which is given in Fig. 846 and a restoration by Marsh of another similar genus in Fig. 847. This was a huge bipedal herbivore, thirty-eight feet long, and head three and a half feet, with curious spoon-bill-like beak and magazines of numerous teeth (two thousand in all), somewhat like those of the Hadrosaur already described (p. 503).

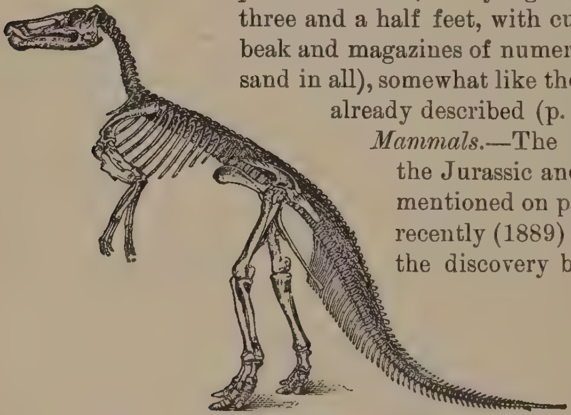

FIG. 847.—Claosaurus annectens (after Marsh), × $\frac{1}{80}$, Laramie, Wyoming.

Mammals.—The great gap between the Jurassic and Tertiary mammals mentioned on page 510 has only very recently (1889) been partly filled by the discovery by Marsh of twenty-four species of mammals from the Laramie. The teeth of two of the most characteristic species are given in Figs. 848 and 849. These very important discoveries of Marsh were supposed to be unique. But in 1890 Lemoine found at Cernay, France, a mammalian fauna in which Metatheres and monotremes, extremely similar to those of the Laramie, are associated with Eutheres characteristic of the lowest Tertiary (Puerco-beds).* Thus the connection of the Laramie with the Tertiary is made still closer. Nevertheless a gap still remains; we still look in vain for the immediate progenitors of the Tertiary mammals. They will doubtless

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* Bulletin, Geological Society of France, vol. xviii, pp. 219, 321 (1890).

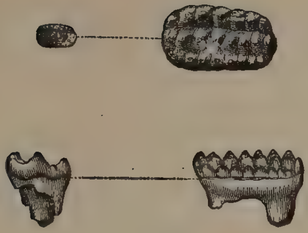

FIG. 848.

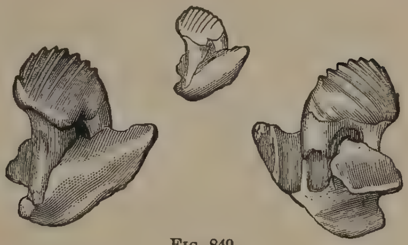

FIG. 849.

FIGS. 848 and 849.—LARAMIE MAMMALS (after Marsh): 848. Cimolomys gracilis, × 3. 849. Halodon sculptus, × 2.

yet be found in the Cretaceous and probably in the Laramie of this or possibly some other country, from which they migrated at the beginning of the Tertiary.

CHAPTER V.

CENOZOIC ERA—AGE OF MAMMALS.

THIS deserves the rank of a distinct *era*, and the corresponding rocks that of a distinct *system*, because there is here a great break in the rock-system, and a still greater break in the life-system. Between the rocks of the Cretaceous and Tertiary there is, in Europe, almost universal unconformity. In America, on the contrary, especially on the Western Plains and in California, there seems to be in some places a continuous series of conformable rocks connecting the two eras (Hayden). *The record seems to be continuous.* Yet here, no less than in Europe, there is at a certain horizon a rapid and most extraordinary change in the life-system. This it seems impossible to explain on the theory of evolution unless we admit *periods of rapid evolution.* The reason why there is no general unconformity in America is, evidently, that the movement here was *continental*, and not mere mountain-making and strata-crushing. Such continental movements, however, would produce very great changes in climate, and therefore in organic forms. The end of the Jurassic was a period of mountain-making, and therefore of unconformity—the end of the Cretaceous, pre-eminently a time of continent-making, and but little unconformity, but very great change of climate. Therefore, although the interval lost in America seems greater at the end of the Jurassic, the change of fauna and flora was far greater at the end of the Cretaceous.

General Characteristics of the Cenozoic Era.—As indicated by the name, modern history commences here; modern types were introduced or became predominant; the present aspect of field and forest commences, and the present adjustment of the relations of the great classes and orders was established. Then, as now, the rulers of the seas were great sharks and whales; the rulers of the land, mammalian quadrupeds; and the rulers of the air, birds and bats. Many of the genera and some of the species of both animals and plants were identical with those still living. The dominant class becomes now Mammals: Reptiles, therefore, in accordance with a necessary law, decrease in size and number, and thus find safety in a subordinate position. In some of these characteristics the Cenozoic era was anticipated in the Upper Cretaceous, in accordance with the law that the first beginnings of each age is in the preceding age.

Divisions.—The Cenozoic era, or age of Mammals, embraces two periods, viz.: 1. The *Tertiary*, and 2. The *Quaternary*. In the *Tertiary* all the mammals are now wholly extinct, but the invertebrate species are some of them still living, and an increasing percentage of living species appears as time progresses. In the *Quaternary* most, though not all, of the mammalian species are extinct, but nearly all (ninety-five or more per cent) of the invertebrate species are living.

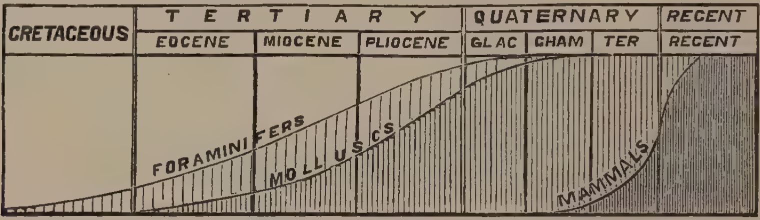

FIG. 850.—Diagram illustrating the Relative Duration of Lower and Higher Species.

These facts are graphically represented in the following diagram, in which the curved ascending lines are the *lines of appearance* of *living* species, and of *extinction* of *extinct* species of *Foraminifera*, of *molluscous shells* and of *mammals*. In each case the lower shaded space represents living species appearing in small numbers, and increasing with the progress of time; and the upper unshaded or less shaded space, previous species gradually dying out and becoming extinct. It is seen that *living* species of *Foraminifera* commenced in the Cretaceous, and very steadily increased in number; those of *shells* commenced in the earliest Tertiary, and increased somewhat more rapidly; while those of *mammals* commenced only in the Quaternary, and increased correspondingly rapidly. Also the *relative proportion* of living and extinct at any time is shown by comparing the amount of space above and below the line at that time. Also the relative *range in time* of low and high species, and the amount of overlapping of successive faunæ are shown.

The mammalian class probably culminated near the end of the Tertiary or during the Quaternary period.

Section 1.—Tertiary Period.

Subdivisions.—We have already stated that the general differential characteristic of this period, as compared with the next, is that all the mammals, and most of the invertebrates, are extinct; but of the latter a percentage, small at first but increasing with the progress of time, are still living. It is upon this *percentage* of living shells that Lyell has based his division of the Tertiary period into three epochs—a Lower, Middle, and Upper Tertiary, or Eocene, Miocene, and Pliocene.

Tertiary period.	Pliocene epoch, or Upper Tertiary = 50–90 per cent living shells.
	Miocene epoch, or Middle Tertiary = 30 per cent living shells.
	Eocene epoch, or Lower Tertiary = 5–10 per cent living shells.

These percentages are expressed graphically in the diagram, Fig. 850. In these, as in the strata of all periods, however, there are certain *characteristic species* by which the epoch may be known, without counting the number of species and calculating the percentage of living. When mammalian species are found, these are especially characteristic of the epoch. Again: Although Tertiary mammalian species are *all* extinct, the genera and families are not *all;* so that the first appearance of living families and genera is also very characteristic of the different epochs.

Rock-System—Area in the United States.—On the *Atlantic border*, going southward, there is no Tertiary, except a small patch on Martha's Vineyard, off the coast of Massachusetts, and another on Long Island, until we reach New Jersey. From this point southward the Tertiary is a broad strip, about one hundred miles wide, bordering the coast, and shown on the map (p. 302) by the space shaded with oblique lines running to the right. It constitutes the low-countries of the Southern Atlantic States. At its junction with the metamorphic region of the up-countries, there are in nearly all the rivers cascades which determine the head of navigation. Here, therefore, are situated many important towns—e. g., Richmond, Virginia; Raleigh, North Carolina; Columbia, South Carolina; Augusta, Milledgeville, and Macon, Georgia. This has been called the *Fall-line.* The same strip of flat lands *borders* also the *Gulf*, expands, in the region of the Mississippi River, northward to the mouth of the Ohio, and then continues around the western border of the Gulf. In the Gulf-border region, however, the Tertiary is in contact below with the Cretaceous, instead of with Archæan, as on the Atlantic border. This whole Atlantic-border and Gulf-border Tertiary is, of course, a *marine* deposit.

In the *interior*, on the Plains and in the Rocky Mountain region, there are enormous areas of *fresh-water* deposit, some Eocene, some Miocene, and some Pliocene, which are of extreme interest.

Among the *Eocene* basins the most remarkable are: 1. The Green River basin. 2. The Uintah basin. Both of these are on the east side of the Wahsatch Mountains, and separated from each other by the Uintah Mountains, one being north and the other south of that range. They were possibly once united, but now separated by erosion. The strata of the Green River basin are 6,000 to 8,000 feet thick.

Among the *Miocene* basins the most interesting are: 1. The *White River basin*, in Nebraska. 2. The *John Day basin*, of Oregon. This latter is 5,000 feet thick, but is largely overlaid by the great lava-flood of the Northwest. 3. Patches of Miocene scattered about in Nevada basin region show that deposits of this age once extended far south into Nevada and Eastern California (King).

Of *Pliocene* basins: 1. *Niobrara* (or Loup-fork) *basin*, occupying partly the same locality as the Miocene *White River basin*, but more extensive, reaching southward in patches almost to the Gulf, and northward into British America. 2. In *Oregon* also there is a Pliocene basin, occupying partly the same region as the previous Miocene. 3. Another discovered by Cope in the basin of the Rio Grande. 4. According to King, the Oregon and Nevada lake-deposit was in Pliocene times greatly extended, so as to cover the whole Basin region, but has been largely removed by erosion or covered by Quaternary deposits.

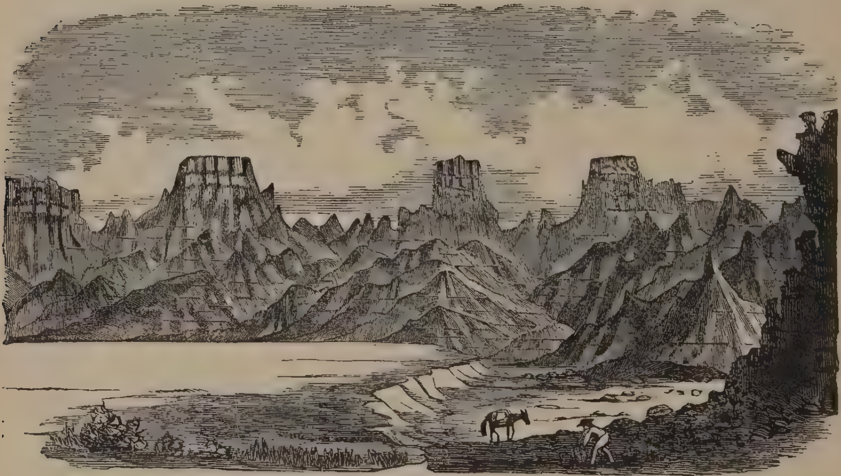

FIG. 851.—Mauvaises Terres, Bad Lands (after Hayden).

All these deposits are imperfectly lithified sand and clays in nearly horizontal position, and many of them have been worn by erosive agencies in the most remarkable way, sometimes into knobs and buttes like potato-hills on a large scale, sometimes into castellated and pinnacled forms, which resemble ruined cities. These are the "*Mauvaises Terres*" or "Bad Lands" of the West (Fig. 851).

On the Pacific coast, a large portion of the Coast Ranges from Southern California to Washington is Tertiary, as are also in many places the lowest foot-hills of the Sierras.

Physical Geography.—From what has been said of the distribution of the rocks of this age, it is easy to reconstruct in a general way the physical geography of the American Continent during the early Tertiary period. In the northern part the *Atlantic shore-line* was probably *beyond* the present line, for there is no Tertiary deposit visible there. The shore-line of that time crossed the present shore-line in New Jersey, then passed along the line of junction of the Tertiary, first with the Cretaceous of New Jersey; then with the Metamorphic, its waves washing shores of Archæan rocks all along the Atlantic coasts, as it does now in the northern portion only; then along the junction of the same again with the Cretaceous of Georgia, Alabama, and Mississippi. The whole low-countries of the Southern Atlantic States and the whole of Florida were then a sea-bottom. The *Gulf of Mexico* was far more extensive than now, and especially it sent a wide bay northward to the mouth of the Ohio. The Mississippi River below that point did not then exist. The Ohio, Arkansas, and Red Rivers emptied by separate mouths into the embayment of the Gulf.

This was at the *beginning*. During the *course* of the Tertiary the shore-line was gradually transferred eastward along the Atlantic, and southward along the Gulf, as shown by the dotted lines introduced in the Tertiary areas in the map on page 302.

In the interior, in the region of the Plains, the Plateau, and the Basin, there were at different times immense *fresh-water lakes*. The places of some of these are indicated on map, Fig. 852, in dotted outline. These outlines, however, are not intended to be accurate. These lakes drained some of them into the Mississippi, some into the Colorado, and some into the Columbia River.

The Pacific shore-line at that time was along the foot-hills of the Sierra Range, and therefore the whole region occupied by the Coast Ranges and the Sacramento and San Joaquin Valleys, and also portions of Western Oregon, were then a sea-bottom with possibly a chain of islands off the coast in the position of the present Coast Range. These facts are roughly represented on map, Fig. 852. The positions of the principal mountain-chains, e. g., Sierra, Wahsatch, Uintah, the eastern border of the Rocky Mountains, and Appalachian, are represented by heavy lines, in order the better to locate the lakes. It will be observed that the continent is *nearly finished*.

Europe is now remarkable for its inland seas. It was much more so in Tertiary times. Many great cities, as, for example, London, Paris, Vienna, are situated on Tertiary strata, partly because these strata are usually found on the borders of continents, and partly because they are often found in the course of great rivers, which once drained lake-basins.

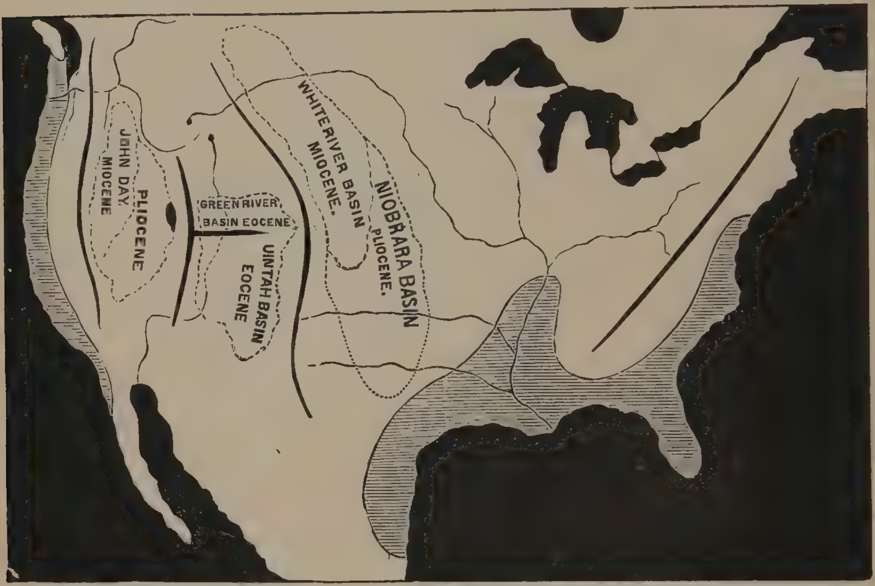

Fig. 852.—Map of Tertiary Times, showing Outline of Coast and Places of Principal Tertiary Lakes.

Character of the Rocks.—The rocks of this period, along the Atlantic border and in the interior Plains and Rocky Mountain region, are mostly imperfectly lithified; but on the Pacific coast they are not only of stony hardness, but in many cases completely *metamorphic.* Much of the rock in the Coast Chain is scarcely distinguishable from the schists of the Palæozoic or still older periods. The reason is evident—metamorphism is closely connected with mountain-making, and mountain-making continued until the end of the Tertiary on the Pacific coast.

Coal.—Again, in the Tertiary rocks we find coal, although more usually in the imperfect condition called lignite. We have already stated that the Rocky Mountain coal-fields are by some referred to the Tertiary. We have referred these to the Laramie. But there are others about which there is as yet no controversy. The *Coos Bay* coal, of Oregon, is probably Miocene-Tertiary. The Nevada coal is Upper Eocene or Lower Miocene. Again, Mr. Selwyn, the Geologist of Canada, has reported large fields of coal on the Qu'Appelle and the

North Saskatchewan Rivers, covering an area of 25,000 square miles, a part, at least, of which he refers to the Tertiary. Much of this coal is of good quality. It seems most probable, however, that this also belongs mostly to the Laramie.

In Europe also an imperfect coal (lignite) is found in the Miocene in considerable quantity.

Petroleum.—In strata of this age occur the petroleum and asphalt so abundant in the Coast Range of South California.

Lava-fields.—The great lava-fields of the western part of the continent belong mostly to the Tertiary: (1) The great Lava-flood of the Northwest (already spoken of on p. 218), which covers Northern California, Northwestern Nevada, a large part of Oregon, Washington, and Idaho, and extends far into Montana and British Columbia. This is one of the largest fields in the world. (2) The lava-field of the Coast Range of California, especially in Napa and Lake Counties, and northward into Oregon. (3) Enormous fields in the Plateau and Basin regions. The Tertiary was undoubtedly a period of exceptional volcanic activity, but it must be remembered that earlier outpourings have been mostly removed by erosion and only their roots left in the form of dikes. Even Tertiary eruptions have in many cases been largely thus removed. We have a striking illustration of this in the Mt. Taylor group, which, according to Dutton, consists of mere wrecks of Tertiary volcanoes. During later Tertiary times not only their overflows, but the strata through which they came up, have been swept clean away, and only the cores of lava filling their craters have been left as "necks" standing above the surrounding country as witnesses of the amount of general erosion.

Life-System.

General Remarks.—We have already spoken of the great and rapid change in the life-system between the Cretaceous and the Tertiary, even where the two series of rocks are continuous and conformable. This indicates, undoubtedly, a more rapid rate of evolution at that time. But it also indicates, as one cause of this rapid evolution, a *migration* of species brought about by changes in physical geography and climate, and the imposition of one fauna and flora upon another, and the extermination or else modification of one by the other. It is difficult to conceive of these sudden changes taking place otherwise. We shall speak more fully of this important point under the Quaternary.

The general character of the life-system of the Tertiary, as already said, was in the main similar to the present. Nearly all the genera and many of the species of plants and invertebrate animals were the same as now, and the difference in aspect would hardly be recognized by the popular eye; it was certainly not greater than now exists between different countries. It is only among Mammals that the difference was very conspicuous.

Plants.

Among plants, nearly all the *genera* of Dicotyls, Palms, and Grasses were the *same as now*, though most of the *species* are extinct. The cereals, however, were not yet introduced. *The genera were the same as now*, but *not in the same localities.* On the contrary, the vegetation indicated a much warmer climate than exists now in the same localities. For example, if we regard the Lignitic as Eocene-Tertiary (instead of *Cretaceous*), as do paleontological botanists generally, then of more than 300 species of plants found a very large proportion were Palms, and many of them of great size; and among the Dicotyls many, like Magnolias, indicated a warm climate. Lesquereux thinks the climate of Fort Union was *then* similar to that of Florida and Lower Louisiana *now.* There has been a southward migration of forms since that time. Again, in *Eocene* times there were fifteen species of Palms in Europe; and in the Tyrol the flora, according to Von Ettingshausen, indicated a temperature of 74° to 81° Fahr., and many of the plants are Australian in type. In the Pliocene, on the contrary, many European plants were like those in America at the present time.

During *the Miocene*, Europe was covered with evergreens such as could grow now only in the southernmost part; and that even as far as Lapland, and Iceland, and Spitzbergen. It has been estimated that the Miocene flora indicates a mean temperature of 12° to 15° higher than now exists in Middle Europe. In America, during the same epoch, Sequoias almost identical with the Big Tree and Redwood of California; and *Libocedrus*, one of them identical with the *L. decurrens* of California; and Magnolias similar to the *M. grandiflora* of the Southern Atlantic States; and *Taxodium distichum*, the cypress of the swamps of Carolina and Louisiana, all existed in Greenland, and most of them also in Northern Europe, and Iceland, and Spitzbergen, and even Grinnell Land, 81° north latitude. Heer estimates the temperature of Greenland in the Miocene as 30° higher than now. Evidently there was no polar ice-cap at that time. The testimony of the plants is entirely confirmed by that of the fossil shells. According to Dall, the mean temperature of the Sea of Okhotsk in Miocene time must have been 60° to 70°, where now it is 28°. There is little doubt that the luxuriance of vegetation everywhere was far greater than now.

It is interesting to note again *remnants* of former types of vegetation now almost extinct. According to Ward, there are about fifty species of Sequoias known. They ranged in time from the Lower

Cretaceous to the present and in space from Greenland and Spitzbergen on the north to Chili and New Zealand on the south, but their culmination in number was in the Tertiary. Only two remain, and these only in isolated patches in California.

These facts show not only a warm but a uniform climate, and probably also a *connection in high latitudes between the American and European Continents.* A similar connection, shown also by the vegetation, probably existed between Alaska and the Asiatic Continent at that time. The accompanying figures represent some of the Dicotyls and Monocotyls of American and European Tertiary.

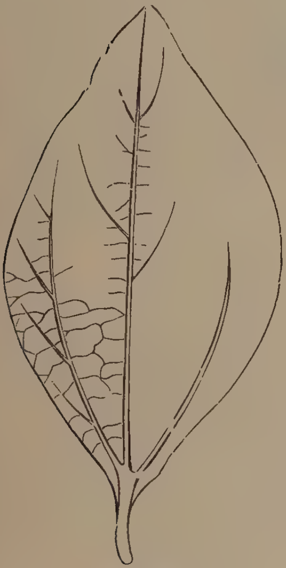
FIG. 853.

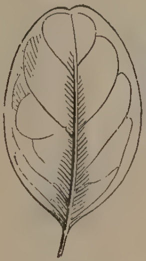
FIG. 854.

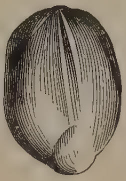
FIG. 856.

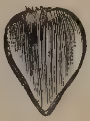
FIG. 857.

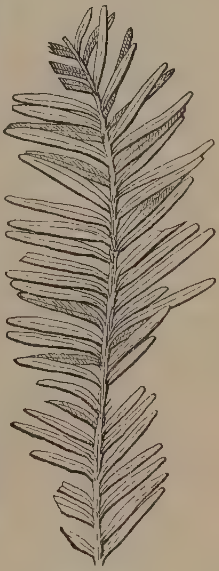
FIG. 859.

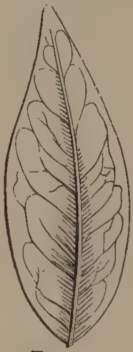
FIG. 855.

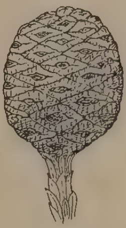
FIG. 858.

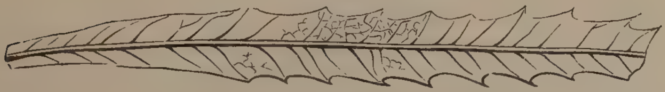
FIG. 860.

FIGS. 853-860.—AMERICAN TERTIARY PLANTS (after Safford and Lesquereux): 853. Cinnamomum Mississippiense. 854. Quercus crassinervis. 855. Andromeda vaccinifoliæ affinis. 856. Carpolithes irregularis. 857. Fagus ferruginea.–Nut. 858. Fruit of Sequoia Langsdorfii (after Heer). 859. Leaf of Sequoia Langsdorfii (after Heer). 860. Quercus Saffordi.

Another conclusion to be drawn from the foregoing facts is that, in the race of evolution, Europe seems to have distanced most other countries. The Australian flora is now only where the European flora was

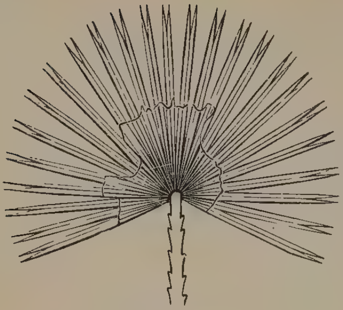

FIG. 861.

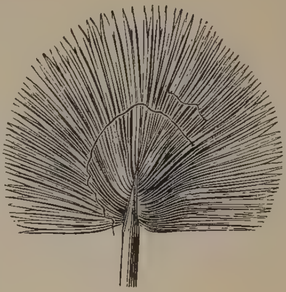

FIG. 862.

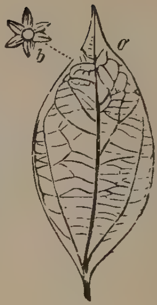

FIG. 864.

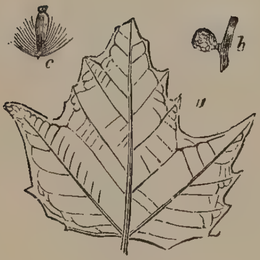

FIG. 863.

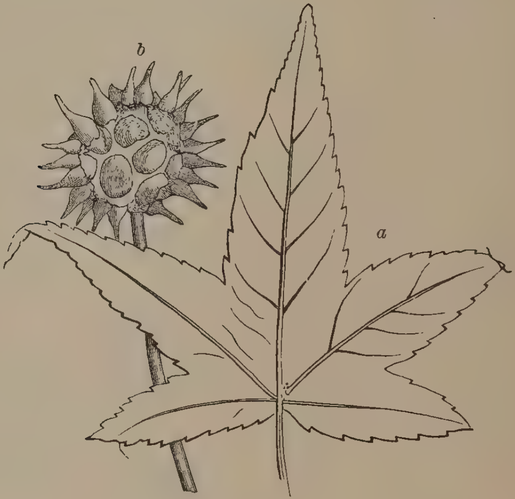

FIG. 867.

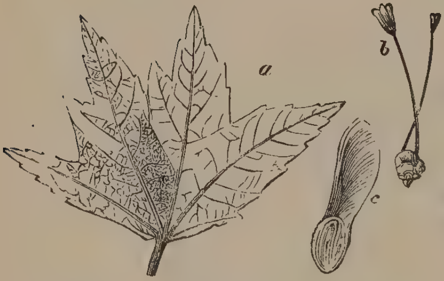

FIG. 865.

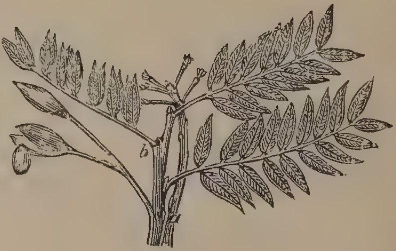

FIG. 866.

FIGS. 861–867.—PLANTS OF EUROPEAN TERTIARY: 861. Chamærops Helvetica. 862. Sabal major. 863. Platanus aceroides: *a*, Leaf; *b*, Core of a Cluster of Fruits; *c*, Single Fruit. 864. Cinnamomum polymorphum: *a*, Leaf; *b*, Flower. 865. Acer trilobatum: *a*, Leaf; *b*, Flower; *c*, Seed. 866. Podogonium Knorrii. 867. Liquidambar Europeum, from Œningen: *a*, Leaf; *b*, Fruit (after Heer).

in Eocene times, and the American flora now where the European was in the Pliocene. The probable reason is that, in Europe, in these later geological times,* changes of physical geography and climate, and consequent migrations of species, were more frequent, and the struggle for life more severe. Australia especially, probably on account of its isolation, has advanced more slowly than most other countries. Many remnants of extinct faunas and floras exist there still.

Still another conclusion is that the floras of Europe, America, and Australia were far *less differentiated* from one another then than now.

It is also very noteworthy that while Sequoias and Cypresses and Taxodiums were so abundant, we find no *true Pines* until the Mid-Tertiary. These are the latest as they are also the most specialized of Conifers.

Diatoms.—If the highest of plants—Dicotyls and Monocotyls—were abundant, probably more abundant than now, so also were the lowest order of uni-celled plants—the *Diatoms.* Immense deposits, consisting wholly of the silicious shells of these microscopic plants, are found in the Tertiary. In Europe the Bohemian deposit is celebrated. It is fourteen feet thick, and every cubic inch of the material, accord-

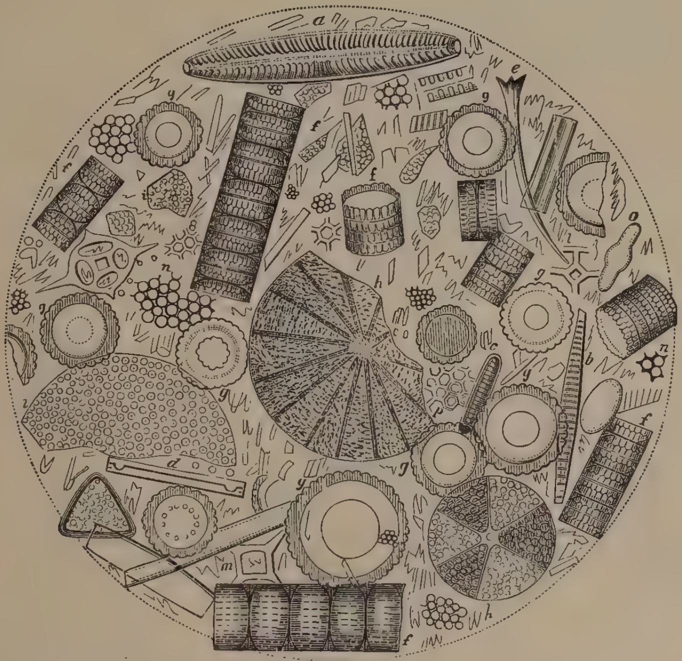

Fig. 868.—Microscopic View of Richmond Infusorial Earth (by Ehrenberg).

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* In *Cretaceous times* the flora of America seems to have been more advanced than that of Europe.

ing to Ehrenberg, contains 40,000,000,000 shells. The Richmond (Virginia) deposit is equally well known. It is thirty feet thick, and many miles in extent. Similar deposits are especially abundant in California. They are found in at least a dozen localities where the Tertiary rocks prevail, as, for example, at San Pablo, in Shasta County, and near Monterey, the last deposit being fifty feet thick.

Some of the more remarkable forms of Diatoms are shown in Fig. 868, which is a view under the microscope of the Richmond deposit.

Deposits of this kind are usually called infusorial earths. They may often be recognized, even without microscopic examination, by their soft, *chalky* consistence, their *insolubility* in acids, and their extreme *lightness.*

Origin of Infusorial Earths.—It is well known that mud composed of diatom shells accumulates at the bottoms of ponds, and lakes, and sluggish streams. In the deepest parts of Lake Tahoe, where sediments do not reach, the ooze is composed wholly of infusorial shells. It has been shown, also, by Dr. Blake,* that the deposits from hot springs of California and Nevada, even where the temperature is 163° to 174°, abound in Diatoms of the same species as those found in California infusorial earths. It is probable, therefore, that many of these deposits were made in hot springs and hot lakes, which, judging from the volcanic activity of that time, abounded in California then, even far more than now. Dr. Blake thinks the infusorial earths of California are *Miocene.* In the hot-springs of Yellowstone Park deposits of this kind are now forming over many square miles and are five or six feet thick (page 168).

Animals.

As already stated, among Invertebrates there was a general similarity to the present fauna. Nearly all the genera and many of the species were identical with those still living. The relation between the various orders which prevail *now* commenced *then.* The present basis of adjustment was *then* established. Then, as now, Brachiopods and Crinoids were nearly all gone, Echinoderms were nearly all free, and Bivalves were nearly all Lamellibranchs. Then, as now, naked Cephalopods and short-tailed Crustaceans greatly

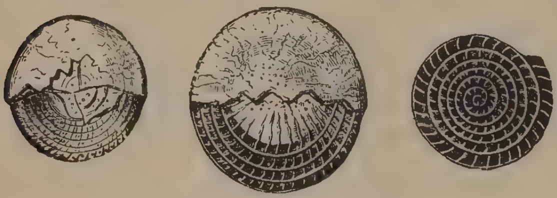

FIG. 869.—Nummulina lævigata.

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* American Journal of Science, Part III, vol. iv, p. 148.

predominated. A glance at the following figures of Tertiary shells (Figs. 870–883) will show the general resemblance to those of the present seas.

In regard to the Invertebrates, there are only three or four points of sufficient importance to arrest our attention in a rapid survey.

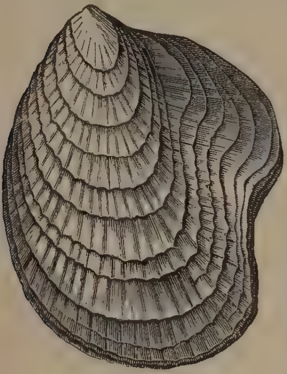

FIG. 870.

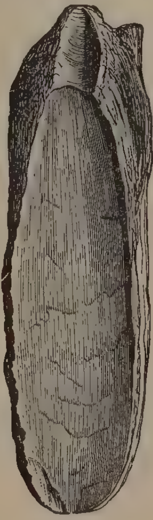

FIG. 871.

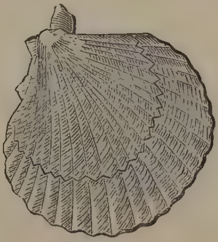

FIG. 872.

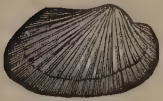

FIG. 873.

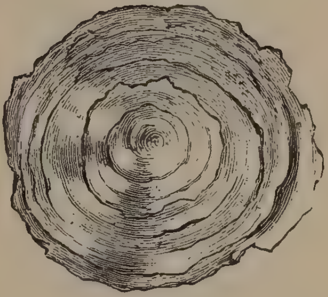

FIG. 874.

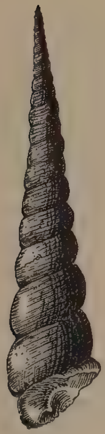

FIG. 875.

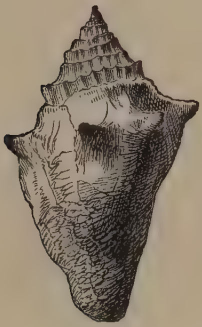

FIG. 876.

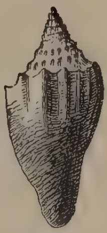

FIG. 877.

FIGS. 870–877.—EOCENE TERTIARY SHELLS: 870. Ostrea sellæformis (after Meek). 871. Ostrea Georgiana (after Meek). 872. Pecten nuperum (after Wailes). 873. Anomalocardia Mississippiensis (after Conrad). 874. Umbrella planulata (after Wailes). 875. Turritella alveata (after Wailes). 876. Volutalithes dumosa (after Wailes). 877. Volutalithes symmetrica (after Wailes).

Among *Rhizopods*, Nummulites (a foraminifer, Fig. 869) abounded to an extraordinary degree. Eocene strata, many thousand feet thick, are formed of these shells. The Nummulitic limestone of the Alps extends eastward to the Carpathians, westward to the Pyrenees, and southward into Africa. It was largely quarried to build the Pyramids of Egypt. It occurs also extensively in Asia Minor and in the Himalayas.

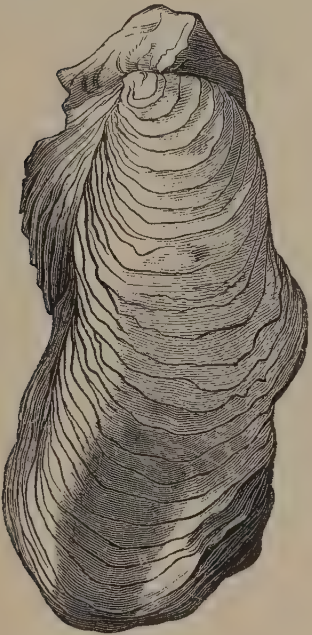

FIG. 878.

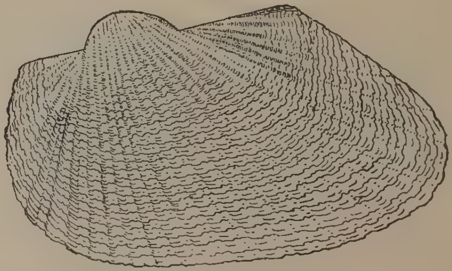

FIG. 879.

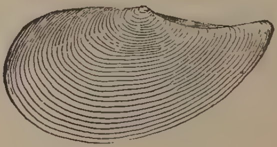

FIG. 881.

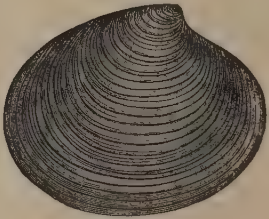

FIG. 880.

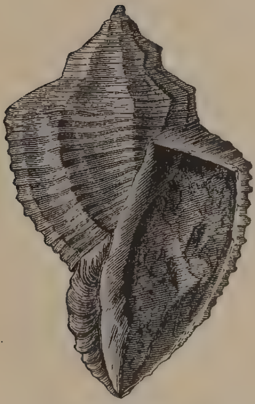

FIG. 882.

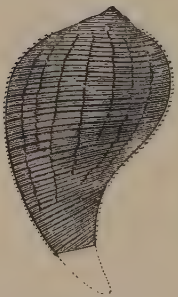

FIG. 883.

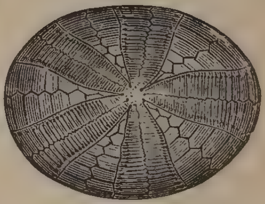

FIG. 884.

FIGS. 878-884.—CALIFORNIA MIOCENE SHELLS (after Gabb): 878. Ostrea titan, $\times \frac{1}{3}$. 879. Arca macrodonta (Conrad). 880. Venus pertenuis. 881. Yoldia impressa (Conrad). 882. Cancellaria vetusta. 883. Ficus pyriformis. 884. Echinarachnius Brewerianus.

This limestone occurs in the Alps 10,000 feet, in the Pyrenees 11,000 feet, and in the Himalayas 15,000 and even 19,000 feet above the sea-level. We see, then, the immense changes which have occurred by mountain-making since the Eocene.

Among *bivalve shells*, common forms of the present day, such as the oyster, the clam (*Venus*), the scallop-shell (*Pecten*), etc., were very numerous, and some of very large size. Oysters especially seemed to have reached their maximum development in the Tertiary. The *Ostrea Georgiana* (Fig. 871) was ten inches long and four wide; the *Ostrea Caroliniensis* was of equal size, but shorter and broader. A specimen of the *Ostrea titan* of California and Oregon now lies before us, which by measurement is thirteen inches long, eight wide, and six thick (Fig. 878), and a specimen of *Pecten cerrocensis* of California, a Pliocene species, nine inches across. Among univalves also nearly all the forms are familiar. The illustrations are taken from the Eocene and Miocene. The Pliocene shells are almost undistinguishable from living shells, except by the practiced eye. It seems useless to give them in an elementary work.

Insects.—There are several interesting points connected with this class which must not be omitted. We have usually found insects abundant in connection with luxuriant vegetation. During the Miocene, phenogamous vegetation was even more abundant than now; there was also extreme fullness of insect-life. All orders, even the highest, viz., Lepidoptera (butterflies—Fig. 889) and Hymenoptera (bees, ants, etc.—Fig. 885), were represented.

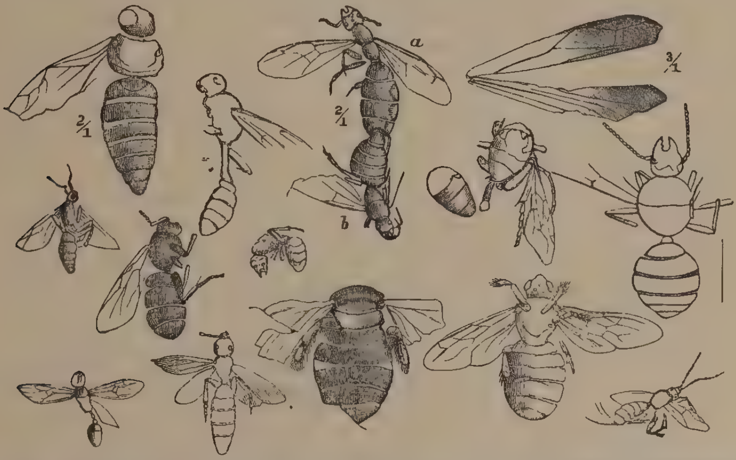

FIG. 885.—INSECTS OF EUROPEAN MIOCENE (after Heer): *a*, Apis Adamitica; *b*, Ponera veneraria male, *b′* female; *c*, Vespa atavina; *d*, *d*, Ammophila inferna; *e*, Imhoffia pallida; *f*, *f′*, *f″*, Formica lignitum—female, male, and worker; *g*, Myrmica tertiaria; *h*, Ichneumon infernalis; *i*, Xylocopa senilis; *k*, Bombus Jurinei; *l*, Scalea saussureana.

In the Miocene of Europe, 1,550 species of insects have been found; and of these more than 900 species at Œningen in a stratum only a few feet thick (Lyell). In places the stratum is black with the remains of *insects*. The same stratum is also full of leaves of *Dicotyls*, of which Heer has described 500 species. Mammalian remains and fishes are also found in them.

It is interesting to inquire into the conditions under which these strata were formed and filled with these remains. On Lake Superior, at Eagle Harbor, in the summer of 1844, we saw the white sands of the beach blackened with the bodies of insects of many species, but mostly beetles cast ashore. As many species were here collected in a few days, by Dr. J. L. Le Conte, as could have been collected in as many months in any other place. The insects seem to have flown over the surface of the lake; to have been beaten down by winds and drowned, and then slowly carried shoreward and accumulated in this harbor, and finally cast ashore by winds and waves. A small river emptying into the harbor carried also many beetles and ants. Doubtless, at Œningen, in Miocene times, there was an extensive lake surrounded by dense forests, through which ran a small river emptying into the lake; and the insects drowned in its waters, and the leaves strewed by winds on its surface, were cast ashore by its waves. Heer believes also that carbonic-acid emissions helped to destroy, and deposits of carbonate of lime to preserve, the insects. Over five hundred of the Œningen insects were beetles.

Among the insects found at Œningen, Switzerland, and Radoboj, Croatia, are a great many *ants* (Fig. 885). In all Europe there are now about fifty species of ants. Heer found in the Miocene of Œningen and Radoboj *more than* 100 *species.*[*] And, what is very remarkable, nearly all are *winged* ants. Ants of the present day are male, female, and neuter. The males are winged throughout life, and never live in the nests, but soon perish. The females are also winged until they are fertilized; then they drop their wings and live in communities in a wingless condition ever afterward. The neuters are always wingless, and therefore always live in nests or in communities. It is probable that ants at first were only winged males and females, living in the open air like other insects. The wingless condition and the neutral condition are both connected with their peculiar social habits and instincts, and have been gradually developed along with the development of their habits and instincts. It is probable that all these remarkable peculiarities, viz., the wingless condition, the neutral condition, the wonderful instincts, and organized social habits, have been developed together *since the introduction of this order in Early Tertiary.*

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[*] Pouchet, Popular Science Monthly, June, 1873.

In the fresh-water Miocene of Auvergne, France, there is a remarkable stratum called *indusial limestone*, because it is largely composed of the cast-off hollow cases (indusia) of the caddis-worm or larva of the caddis-fly (*Phryganea*), cemented together by carbonate of lime. The number of these cases is countless. The caddis-worm of the present day forms for itself a hollow cylindrical case, of bits of stick or pieces of shell, or sometimes of whole small shells, binding these together by means of a kind of web. In this hollow cylinder it lives, only putting out the head and two or three first joints of the body, to which the feet are attached, in walking. When they complete their metamorphoses, they leave their cases. Fig. 888 is a recent caddis-worm with its case of small shells stuck together; Fig. 887 are indusia of the Miocene caddis-worm; and Fig. 886 is the limestone in place, *a* being the indusial layer.

In Auvergne, in Miocene times, there existed a shallow lake, in which carbonate of lime was depositing, as in many lakes of the present day. In this lake lived myriads of caddis-worms, and their indusia accumulated for countless generations.

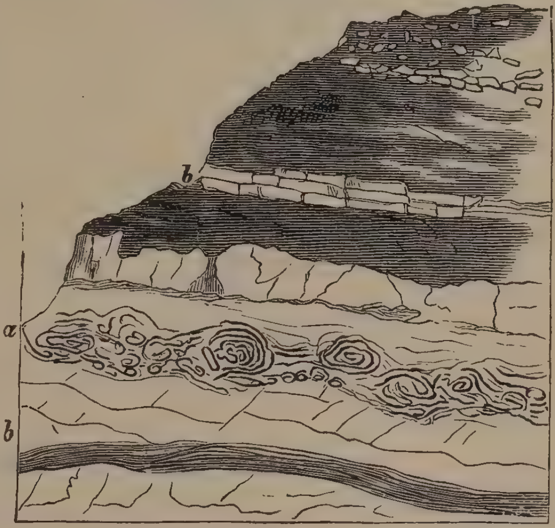

Fig. 886.

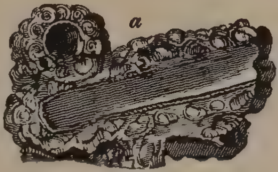

Fig. 887.

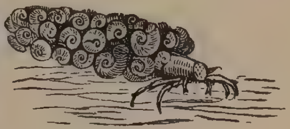

Fig. 888.

Figs. 886–888.—886. Indusial Limestone interstratified with Fresh-Water Marls. 887. A Portion (natural size) showing the Phryganea Cases. 888. Recent Larva of a Phryganea, with its Case.

In the Tertiary strata, about the shores of the Baltic, and also in Sicily, in Asia Minor, and several other localities usually associated with lignite, are found masses of amber. This substance is a fossil resin of several species of Conifer, especially *Pinites succinifer*. It is often quite transparent, and inclosed within may be seen perfectly preserved insects of many kinds. Over 800 species of insects and fragments of many species of plants have been found thus inclosed. The degree of preservation is marvelous; even the most delicate parts, the slender legs, the jointed antennæ, and the gauzy wings are perfect. The manner in which these insects were entangled, inclosed, and preserved, may be easily observed even at the present day. The gum issuing from Conifers is at first in the form of semi-liquid, transparent tears. Flies, gnats, etc., alighting on these, stick fast, and by the running down of further exudations are enveloped and preserved forever. The legs, both in the modern and the fossil resin, are often found broken by the struggles of the insects to extricate themselves. The insects of the Tertiary, like the plants, show a decided tropical character.

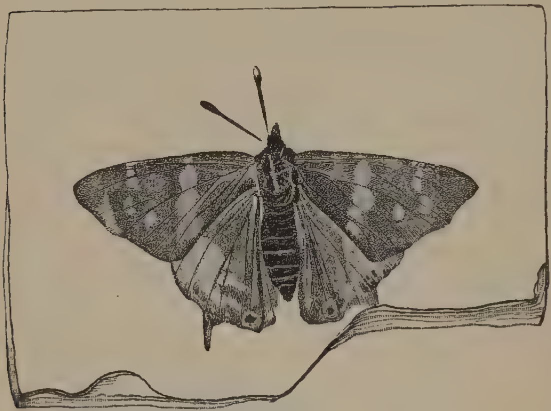
Fig. 889.—Prodryas Persephone (after Scudder).

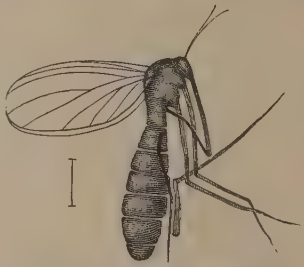
Fig. 890.—Sackenia arcuata, from Tertiary of Utah (after Scudder).

But probably the richest beds in insects yet found are at Florissant, Colorado. Here fresh-water shales of *Green River* age are black with remains of insects of all orders now existing. According to Scudder,* about 1,000 species are recognizable, besides many plants, several fishes, and a bird with feathers preserved. Of

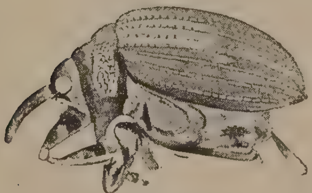
Fig. 891.—Apion refrenatum, × 12 (after Scudder).

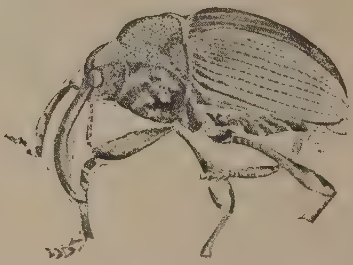
Fig. 892.—Balaninus minusculus, × 8 (after Scudder).

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* Bulletin of the United States Geological Survey, vol. vi, No 2.

30,000 specimens of insects in all museums, about one half are from this locality. Here, also, as in Europe, Hymenopters and Coleopters are most abundant, and all the species indicate tropical climate. Of one family alone, the Rhyncophora or Weevils (Figs. 891 and 892), 116 species were found, and all entirely peculiar (Scudder). Among the insects found here are seven species of butterflies (only nine species are known from all the rest of the world). A beautifully preserved specimen is shown in Fig. 889. At Florissant, in Eocene times, there was a lake, and insects were cast ashore and accumulated in the manner already described. Other Tertiary lake-deposits in the West are also rich in insects (Fig. 890).

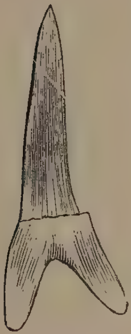
FIG. 893.

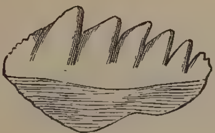
FIG. 894.

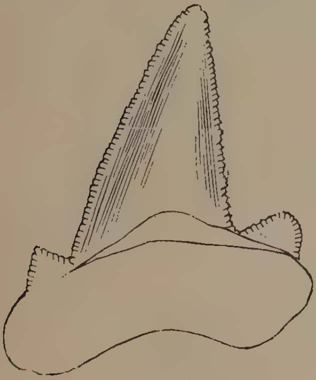
FIG. 895.

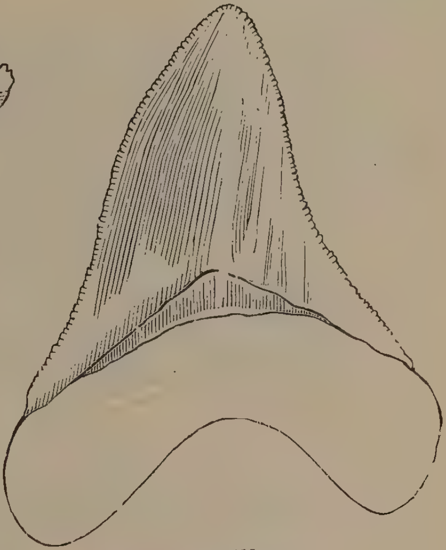
FIG. 896.

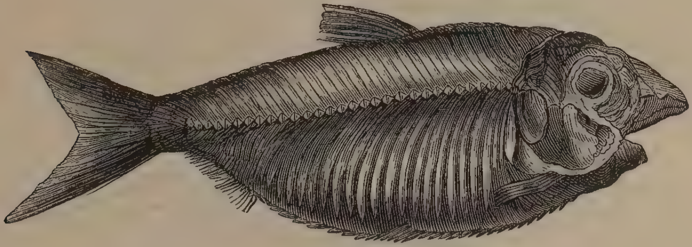
FIG. 897.

FIGS. 893-897.—TERTIARY FISHES—*Elasmobranchs:* 893. Lamna elegans (after Agassiz). 894. Notidanus primigenius (after Agassiz). 895. Carcharodon angustidens (after Gibbes). 896. Carcharodon megalodon, × ½ (after Gibbes). *Teleost:* 897. Clupea alta (after Leidy).

Fishes.—The present relation between the three great orders of Fishes—Teleosts, Ganoids, and Placoids—was first fairly established in the Tertiary. Teleosts were first introduced in the Cretaceous, but only in the Tertiary did they become very abundant. Ganoids, on the contrary, became fewer in number; they sank into their present subordinate position. Among Elasmobranchs, the Hybodonts are gone, the Cestracionts are few in number, but the Squalodonts reach their maximum development, both in number and size. In the marine Tertiary of the Atlantic border, both Eocene and Miocene, sharks' teeth are found in immense numbers, and of very great size. Some of the triangular teeth of the *Carcharodon megalodon* (Fig. 896) are found six and a half inches long and six inches broad at the base. The owners of such teeth must have been fifty to seventy feet long. Some of the more common forms of sharks' teeth of the American Tertiary,

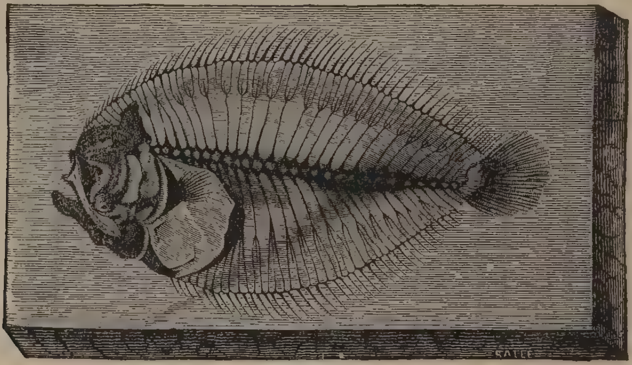

Fig. 898.

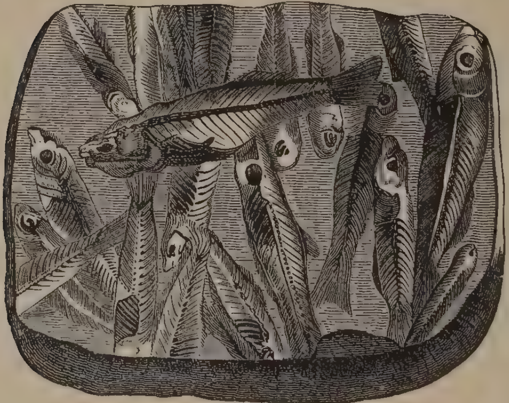

Fig. 899.

Figs. 898, 899.—Tertiary Fishes—*Teleosts:* 898. Rhombus minimus, Lower Eocene. 899. Lebias cephalotes, Miocene.

and Teleosts from American and European Tertiary, are given in the preceding figures.

Amphibians.—As already said, p. 434, the class of Amphibians in the form of Labyrinthodonts culminated in the Trias and became extinct at its end. During the Jura and Cretaceous we have said nothing about Amphibians, although they probably existed in small numbers and in more modern forms. In the Tertiary we again find them somewhat abundant, and now not only the tailed, as before, but also for the first time the highest and most specialized forms, the tailless or frogs. In the Miocene of Europe at Œningen, a Salamandroid Amphibian was found and described in 1728 by Scheuchzer, a physician and naturalist, professor in the University of Altorf. He gave it the title "*Homo Diluvii Testis*," believing it to be the skeleton of a human being destroyed by the deluge. The length was about four feet. It was reserved for Cuvier to show that the fossil was not human, though the name *Andrias Scheuchzeri* (Fig. 900) had become permanently attached to it through Scheuchzer's mistake. A living species of the same genus is now found in Japan, and is of gigantic size. A representation of it is given in Fig. 901, for comparison with its fossil precursor.

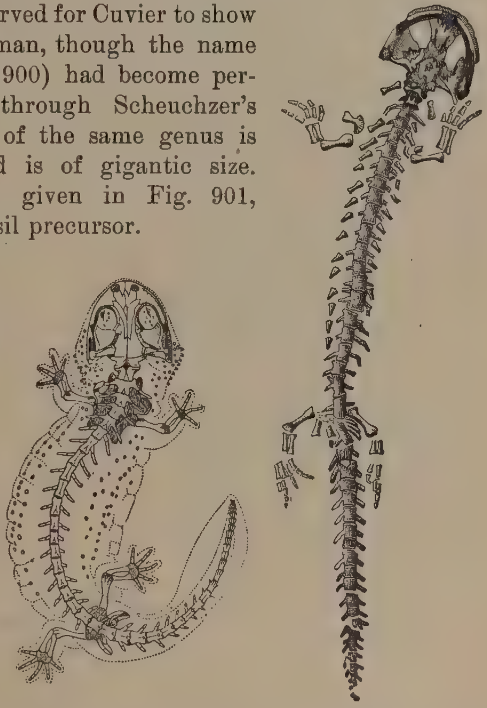
FIG. 901. FIG. 900.

FIGS. 900, 901.—900. Andrias Scheuchzeri, Miocene of Switzerland, × $\frac{1}{10}$ (after Heer). 901. Andrias Japonica, a living Salamander from Japan, × $\frac{1}{10}$ (after Heer).

Reptiles.—The age of Reptiles is past. The huge Enaliosaurs, Dinosaurs, Mosasaurs, and Pterosaurs, are all extinct. Their class is now represented by Crocodiles, Lizards, Turtles, and Snakes, though their place as rulers is supplied by Mammals and Birds. Five species of Snakes, some of them eight feet long, and nine Crocodilians, have been found in the Eocene of Wyoming, and several also in Europe. The Miocene of the Himalayas furnishes a gigantic turtle (*Colossochelys Atlas*), the carapace of which was twelve feet long and eight feet wide, and seven feet high in the roof, and the whole animal was probably twenty feet long. Over sixty species of Tertiary turtles, and eighteen or twenty species of crocodiles, have been described from foreign countries (Dana).

The Crocodilians, the highest living order of reptiles, first appeared in the Triassic, but only in generalized forms—*Stagonolepis*, *Belodon*, etc.—which closely connected them with the Lizards. From this early form Huxley has traced with consummate skill the gradual differentiation of this order, in the position of the posterior nares, the structure of the head and the form of the vertebral bodies, step by step through the Jurassic, Cretaceous, to the Tertiary, where the type reached its perfection.

Birds.—The class of Birds in the Cretaceous was represented only by the *reptilian* birds and ordinary *water*-birds. Now, in the Tertiary, however, the reptilian birds—vertebrated-tailed and socket-toothed—have disappeared. The bird-class is fairly differentiated from the reptilian class, and the connecting links destroyed. Birds of all kinds now appear—land-birds as well as water-birds. In *America*, among land-birds, woodpeckers, owls, eagles, etc., have been discovered and described by Marsh. The number of species found in Europe is much greater than in America. The Miocene beds of Central France alone have, according to Milne-Edwards, afforded seventy species. The Miocene *birds*, like the *plants* and *insects*, show a decided tropical character. "Parrots and Trogons inhabited the woods; Swallows built, in the fissures of the rocks, nests in all probability like those now found in certain parts of Asia and the Indian Archipelago; a Secretary-bird, nearly allied to that of the Cape of Good Hope, sought in the plains the serpents and reptiles which at that time, as now, must have furnished its nourishment. Large Adjutants, Cranes, Flamingoes, Palæolodi (birds of curious forms intermediate between Flamingoes and ordinary Grallæ), and Ibises, frequented the margins of the water where insect-larvæ and mollusks abounded. Pelicans floated on the lakes; and, lastly, Sand-grouse and numerous Gallinaceous birds assisted in giving to this ornithological population a strange physiognomy which recalls to mind the descriptions given by Livingstone of certain lakes in Southern Africa."

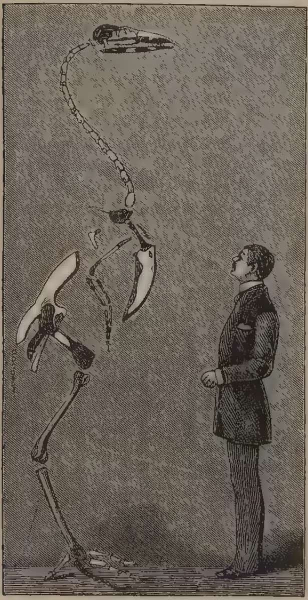

FIG. 902.—Restoration of Gastornis Edwardsii (after Meunier).

But although the class of birds was already well differentiated, yet some remnants of generalized forms still remained. A toothed bird has been found in the London clay (Eocene), and named by Owen *Odontopteryx* (Fig. 903). But this is not a true *socket-toothed* bird.

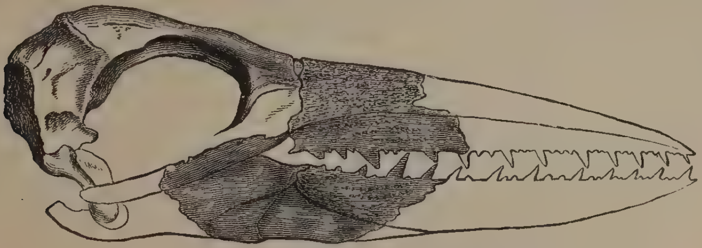

FIG. 903.—Skull of Odontopteryx toliapicus, restored (after Owen).

The so-called teeth, however, are only dentations of the bony edge of the bill. In the Eocene of the Paris basin was found a gigantic bird (*Gastornis*) ten feet in height, combining the characters of a wader with those of an ostrich (Fig. 902).

In 1876 Cope published the discovery of a gigantic bird from the lowest Eocene of the San Juan basin. The *Diatryma gigantea*, according to Cope, combines the characters of the Cursores (ostrich family) with those of the extinct Gastornis of the Paris basin. Judging from its foot, it was double the size of an ostrich. This is the first example of extinct Cursores found in North America (Cope). More recently, however, Marsh has found a gigantic ostrichlike bird (*Barornis regens*) in the Eocene of New Jersey (American Jour. of Sci., 1894).

Mammals—General Remarks.—1. We have already seen that the *evolution* of this class may be traced back to the borders of the Palæozoic. The probable steps are: First, the *Hypotheria*, represented by the Theromorphs, or perhaps a hypothetical generalized type connecting these with the monotremes of the *Permian;* then the *Prototheria*, represented by the generalized monotremes of the *Trias;* then the *Metatheria* of Jurassic and Cretaceous; and, finally, the *Eutheria*, or typical placentals of the Tertiary. 2. But nothing is more noteworthy than the *suddenness* of the appearance of this last term of the series. We find only Mesozoic types even to the *borders* of the Tertiary (Laramie), and then without warning there appears the higher type, Eutheria, of the Tertiary. This might be explained in Europe, where there is un-

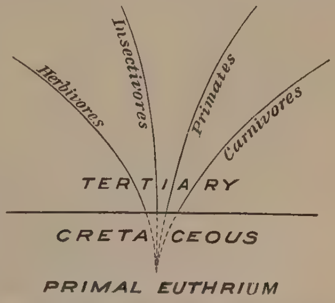

FIG. 904.—Diagram showing Differentiation of Main Orders of Tertiary Mammals.

conformity at this horizon, by the gap in the record; but here in America the record seems almost complete, and yet at the same horizon a great change occurs. It is impossible to explain this unless we admit *times of rapid evolution.* But even this is not sufficient. We must suppose, also, that these new types appeared here in America *by migration* about the end of the Cretaceous from some other country, where we hope yet to find the intermediate links. 3. Their appearance was not only sudden but in *great numbers* and considerable *variety.* In the very lowest beds of the Lower Tertiary (Puerco beds) Cope finds ninety-three species, and already *all the main divisions*, such as Carnivores, Herbivores, Insectivores, and Primates. 4. But, although these main divisions are distinguishable, they are *not yet widely separated*, as we now know them. At that time there were no *typical* Carnivores, Herbivores, etc.; on the contrary, they were all very *generalized types*—i. e., they approached each other very closely, as shown in the diagram (Fig. 904)—so closely, indeed, that if they lived to-day we would probably put them all, or nearly all, in the same family (Zittell). As time went on, not only were they separated more and more by adaptive modification, but also divided into subordinate branches (not shown in the diagram). In order to indicate the fact that these orders were not yet distinctly specialized, it has been proposed to call them *pro*-Carnivores, *pro*-Herbivores, *pro*-Simiæ, etc.—i. e., progenitors of these now widely distinct orders. They were all probably *five-toed Plantigrades*, with *tuberculated molars* (Bunodont), and therefore *Omnivores.* By tracing the divergent lines of the diagram downward, they meet in the Cretaceous in a hypothetical *ancestor*, which was probably an Insectivore. 5. In the course of the Tertiary the mammalian faunas *change completely many times.*

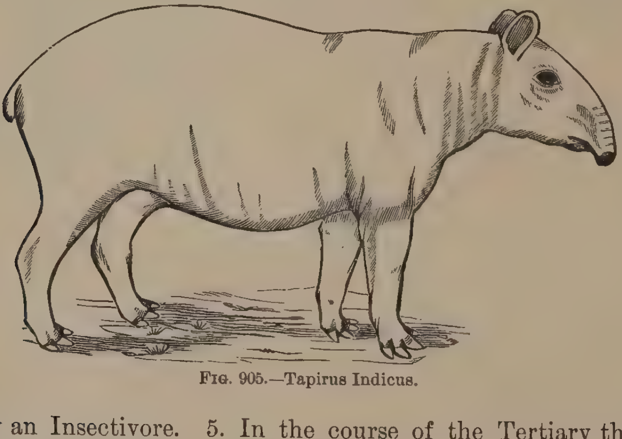

FIG. 905.—Tapirus Indicus.

The Tertiary mammals are of so great interest, from the evolution point of view, that we must dwell upon them somewhat in detail. But it seems impossible to present selections from the immense mass of material at hand in an interesting manner, except by taking a few classic localities from different epochs and different countries, and briefly describing what has been found in each. We will commence with some foreign localities, because these were first discovered:

1. **Eocene Basin of Paris.**—This basin has been made celebrated by the labors of the immortal Cuvier. The discovery in the early portion of the present century of the rich treasures imbedded in the strata of this basin, and the consummate skill with which they were worked up by Cuvier, gave an incredible impulse to geology. Fifty species of mammals, of which forty species were tapir-like; ten species of birds, among which one, the *Gastornis* (Fig. 902), was a huge wader as large as an ostrich; besides reptiles, fishes, and shells in abundance, were discovered. In Eocene times the Paris basin seems to have been an estuary full of shells and fishes, etc., into which the bodies of birds and mammals were drifted. Among the many remarkable mammals we will select two as types, viz., the *Palæothere* and the *Anoplothere.*

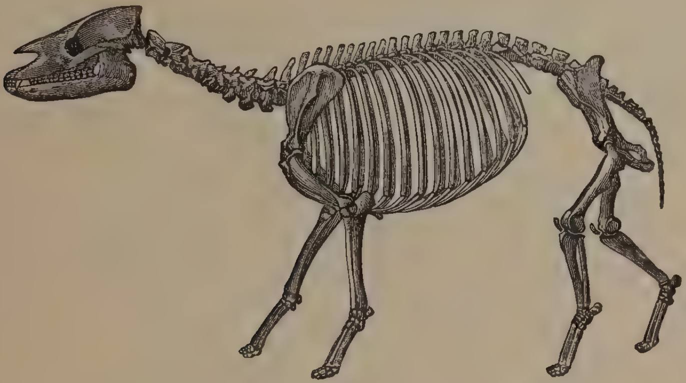

FIG. 906.—Palæotherium magnum, × $\frac{1}{25}$ (after Gaudry).

The Palæothere, like the Rhinoceros and like some of the earlier

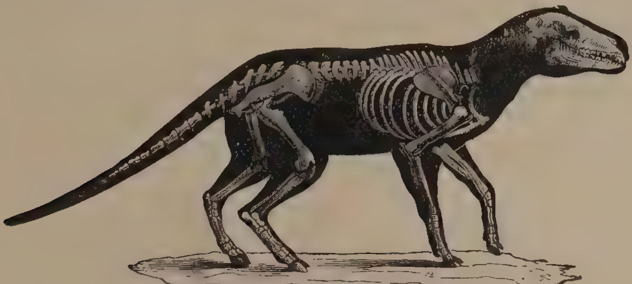

FIG. 907.—Anoplotherium commune, restored.

representatives of the horse family, had three hoofed toes on all the feet. It is usually supposed to have had also the general form and the short flexible snout of a tapir (Fig. 905),* and it is with this family that Cuvier supposed it has its nearest alliance, and his restoration was based on this view. But the discovery of more complete skeletons shows that the neck and limbs were much longer than had been supposed. In general form (Fig. 906) it seems to have been as much like the horse family as the tapirs.

The Anoplothere (Fig. 907) was a slender and graceful animal without snout, and possessing only two toes, like ruminants. Most of its characters, however, allied it to the tapirs. Among these characters was the possession of a *third* rudimental or non-functional toe (Cope) and a full set of front teeth. It was, therefore, a remarkable connecting link between the tapirs and ruminants.

2. **Siwalik Hills, India—Miocene.**—Near the base of the Himalayas occurs a range of hills which are composed of fresh-water uppermost Miocene strata. They are extremely rich in vertebrate and especially in mammalian remains, which have been thoroughly studied by Falconer. One hundred and fifty species of mammals are described from this locality. They are of great variety of forms, both Carnivora and Herbivora, but the latter are most abundant. Among these, perhaps the two most remarkable are *Dinotherium* † and *Sivatherium.*

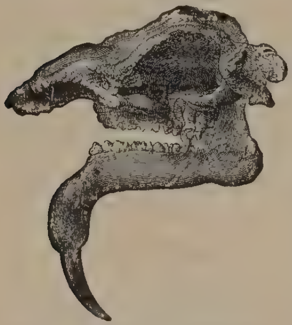

FIG. 908.—Head of Dinotherium giganteum, greatly reduced.

The *Dinothere* has been found also in the European Miocene. It was a huge animal, probably the largest of all land mammals (Gaudry), with a skull three feet long, to which was attached a proboscis. The lower jaw was bent downward, and carried two long, tusk-like teeth, projecting also downward. The whole height of the head, from the points of these lower teeth to the top of the cranium, was five feet.

Recently a perfect pelvis has been found, showing the great massiveness of these bones, and showing also, in these huge animals, the existence, possibly, of *marsupial bones.*‡ This strange animal combined, in the structure of its head, the characters of Elephant, Hippopotamus, Tapir, and Dugong; but it also had affinities with marsupials. It was *the earliest and probably the largest of Proboscidians.*

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* The tapir has three toes on the hind-foot and four on the fore-foot, but the outer one is small and not functional.

† The Dinothere is found in the Miocene of India, though not at Siwalik.

‡ American Journal of Science, Series II, vol. xxxviii, p. 427.

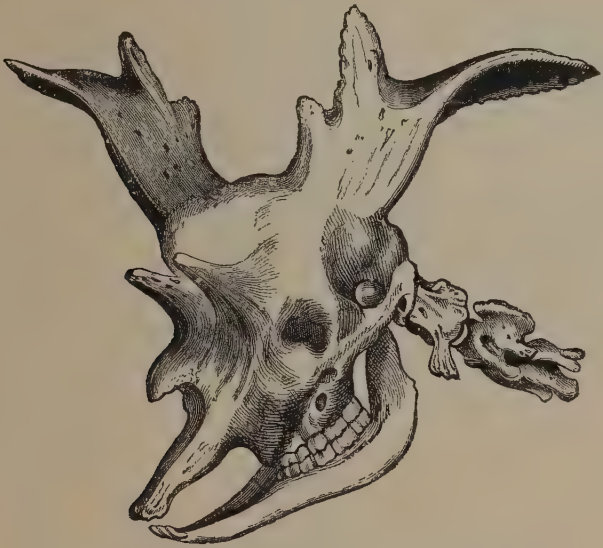

FIG. 909.—Head of a Sivatherium giganteum, greatly reduced.

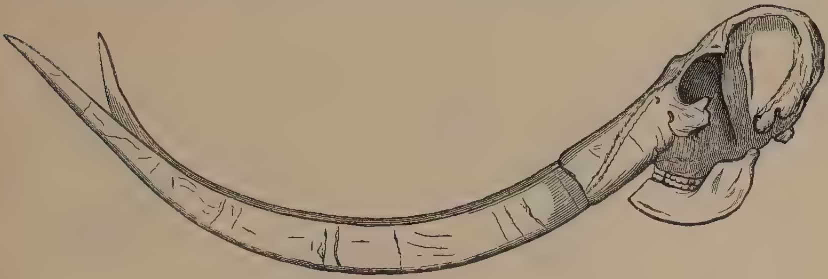

FIG. 910.—Elephas Ganesa, × $\frac{1}{32}$ (after Falconer).

The *Sivathere* was a *four-horned antelope*, of elephantine size and some elephantine characters. The four-horned antelope of the present day lives in the same locality, but is a comparatively small animal, with two short conical horns from the front part of the frontal bone, and two somewhat longer ones in the usual place on the back part of the same bone. The *Sivathere*, on the other hand, was of elephantine height, though of slenderer form, with two short conical horns in front, and two large, palmately branching ones behind. The form of the nose-bones suggests the existence of a snout. The feet and legs were clearly those of a ruminant. It seems to have combined the characters of a Ruminant and a Pachyderm. The *Bramathere* was a similar animal, of equally gigantic size, found in strata of the same age.

In the same locality were found also three species of Mastodons, seven species of Elephants, one of them *E. ganesa* (Fig. 910), remarkable for the prodigious length and size of its tusks; three species of the Horse family; five species of Rhinoceros; four to seven species of Hippopotamus, and three species of hog; also, Anoplotheres, Camels, Camelopards, Oxen, Sheep, Antelope, Musk-ox, Monkeys, etc.; also, many Reptiles, among which were narrow-nosed Crocodiles, like the *Gavials*

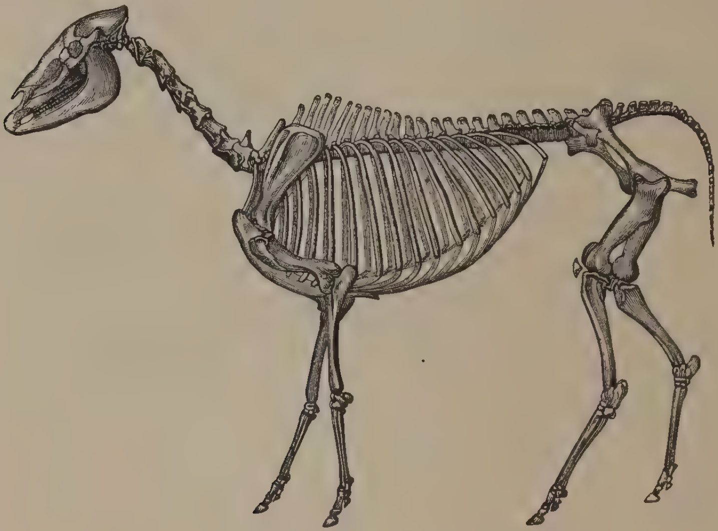

FIG. 911.—Skeleton of Hipparion gracile, restored (after Gaudry).

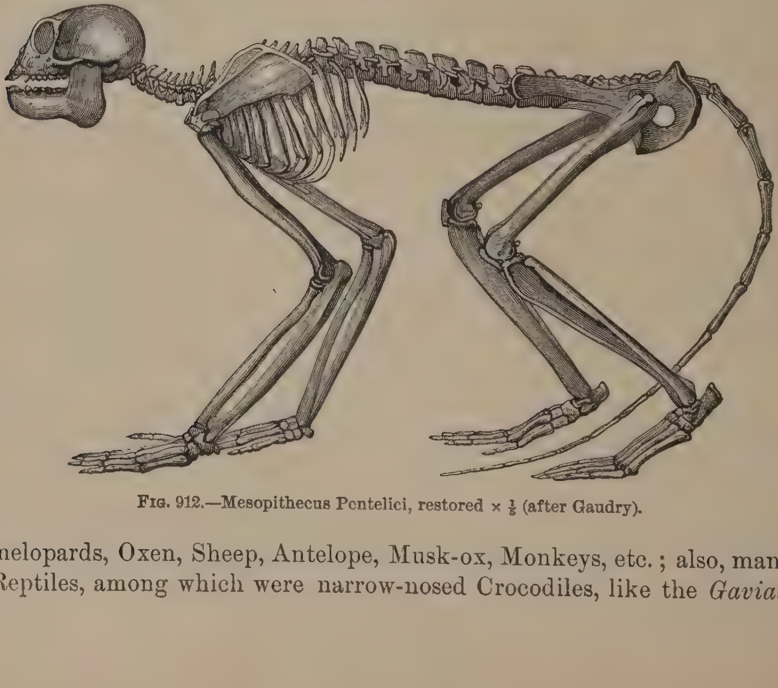

FIG. 912.—Mesopithecus Pentelici, restored × ⅛ (after Gaudry).

now living in the Ganges, and the huge Turtle, *Colossochelys*, already mentioned (p. 539).

The most characteristic representative of the Horse family in the Old World Miocene was a three-toed animal called *Hipparion.* A restoration of this graceful creature is given in Fig. 911.

In the Miocene and Pliocene of Europe are first found remains of that most destructive of carnivores, the saber-toothed tiger—*Machairodus* (Fig. 913). In the Miocene of Europe, also, the first *true Monkeys* (Fig. 912) were introduced (Flower). Before this, there were only lemurs or Prosimiæ.

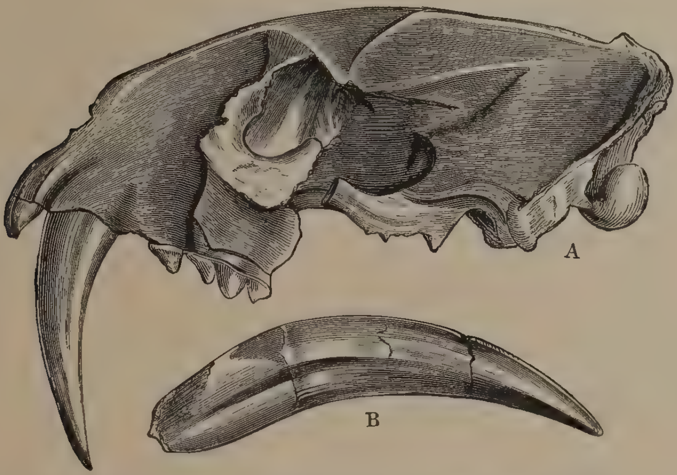

FIG. 913.—*A*, Skull of Machairodus cultridens, without the lower jaw, reduced in size; *B*, Canine Tooth of the same, one half the natural size. Pliocene, France.

Perhaps it is well to call attention to the fact that, while the tapir-like Pachyderms predominate in the *Eocene*, the huge forms, e. g., Rhinoceros and Hippopotamus family, and Proboscidians, were first introduced and immediately became abundant in the *Miocene.*

3. **Upper Eocene of Patagonia.**—The richness of the Tertiary and Quaternary of the southern part of South America almost exceeds belief. Ameghino has collected 50,000 specimens, among which he finds 750 species. The most wonderful of the different horizons there discovered is the *Pyrotherium beds*, which is probably Upper Eocene. In these beds have been found 220 species of mammals, besides many strange birds, and all entirely peculiar to this region. In the *Pyrotherium*—an animal of huge dimensions—Ameghino thinks he finds the long-sought ancestor of the Proboscidians, although it has affinities also with many other families, even with the gigantic Kangaroo, *Diprotodon*, of the Australian Quaternary (p. 612). Still more wonderful are the gigantic

flightless birds found in the same beds. One of these—*Phororachus longissimus*—was ten feet high, and far more massive than the Dinornis and Epiornis of the Quaternary of New Zealand and Madagascar (p. 631). And still more strange, instead of the small head of Dinornidæ, it carried an enormous head, twenty-six inches long and more massive than that of any living mammal except the Elephant, the Rhinoceros, and Hippopotamus. It is probable that these wonderful discoveries will fill many gaps in the history of the development of mammals. The great distinctness of this early fauna plainly points to South America as a distinct center of origin of many mammalian forms.

North American Localities.—4. Marine Eocene of Alabama.—We select this as an example of American marine Eocene. At *Claiborne*, Alabama, according to Lyell, there occur no less than 400 species of *shells*, besides many *Echinoderms*, and abundance of *sharks' teeth*. But the most remarkable remains found there are those of an extinct whale—*Zeuglodon cetoides*—so called from the yoke-like form of the double-fanged molar teeth, which were six inches in length (Fig. 914). The skull was long and pointed (Fig. 915), and set with the double-fanged teeth behind and conical ones in front. The vertebræ, which are in such abundance that they are used for making fences and even burned by farmers to rid the fields of them, are, some of them, eighteen inches long and twelve inches in diameter (Dana), and the vertebral column has been found in place nearly seventy feet long (Lyell). The animal must have been more than seventy feet long, and the remains of at least forty individuals have been found (Lyell). They have been found in southern Georgia as well as in Alabama, and probably their range was quite extensive.

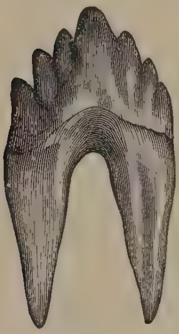
FIG. 914.—Tooth of Zeuglodon cetoides, × $\frac{1}{4}$ (after Gaudry).

This animal is peculiarly interesting as the first appearance of the very distinct order *Cetacea*. No intermediate links have yet been found connecting this with other orders of mammals, or with the great reptiles. And yet, from their large size and marine habits, they are more likely than land mammals to have been found, if they existed

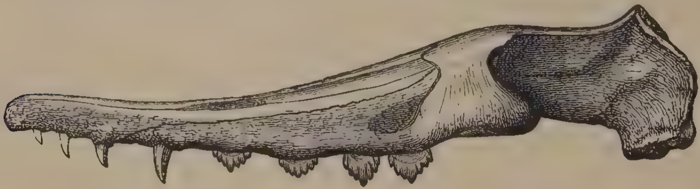
FIG. 915.—Head of Zeuglodon cetoides, × $\frac{1}{16}$ (after Gaudry).

in earlier or Cretaceous times. The origin of whales is not known, although they probably came from *land mammals by retrograde changes adapted for aquatic life.*

Lake Basins of the Interior.—The Atlantic and Gulf border strata are of course all marine, and therefore contain very few land-animals. It is to the *fresh-water basins* of the *interior* that we must look for a full record of the mammalian fauna of America in Tertiary times. These basins furnish the fullest and most continuous record of the whole Tertiary which has ever yet been found. The Early Tertiary fauna of America was wholly different in species and in genera, and even largely in families, from that of Europe. This shows that the two continents were then as now *widely* separated, or at least with communication difficult. It will be best to take them in the order of their age, as we can thus best show the evidences, if any, of derivation of the later from the earlier faunæ.

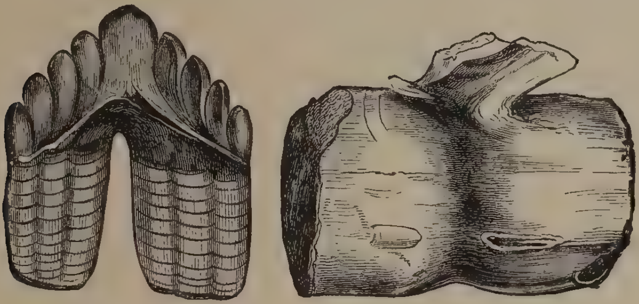

Fig. 916.—Vertebra and Tooth of Zeuglodon cetoides, reduced.

5. **San Juan Basin—Puerco Beds—Lowest Eocene.**—In these, the very lowest part of the Lower Eocene—so low that they are regarded by some even as partly Laramie—Cope has found a great number of most extraordinary mammals, more generalized than any before known. These earliest true mammals seem to have been very abundant, for, out of 106 species of vertebrates found, 93 were mammals. They represent already all the main divisions of the Mammalian class. Besides marsupials continued from the Mesozoic, there were Carnivores, Herbivores, Insectivores, and Lemurine Primates; but in forms so generalized that they scarcely deserve these names, and may well be called *Pro*-Carnivores, *Pro*-Herbivores, etc., or progenitors of these now widely-distinct orders. The remains of these animals are not so perfect as those on higher horizons. We select for illustration an almost perfect hind-limb of the *Periptychus* of Cope, one of the most generalized of known animals. It is seen that the foot-structure is perfectly generalized and the tread completely plantigrade. It is an admirable example of the primitive foot.

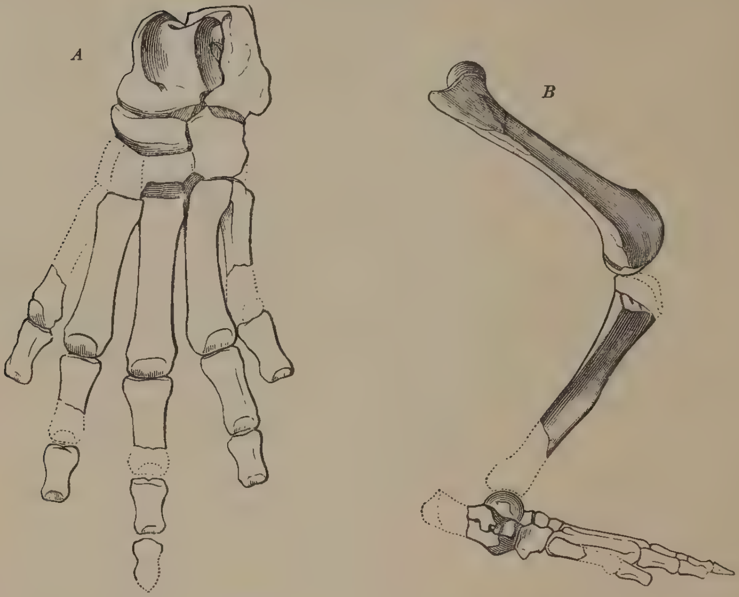

FIG. 917.—Periptychus Rhabdodon: *A*, Hind-foot, × ⅓; *B*, Hind-limb, × ¼ (after Osborn).

6. **Green River Basin—Wahsatch Beds—Lower Eocene.**—Immediately above the last, but still in the Lower Eocene, is found another mammalian fauna equally abundant in species and equally remarkable, but almost wholly different. From this fauna we select two, *Phenacodus* and the *Coryphodon* (peak-tooth). The *Phenacodus* (Fig. 918) is certainly one of the most generalized mammals known. It may be

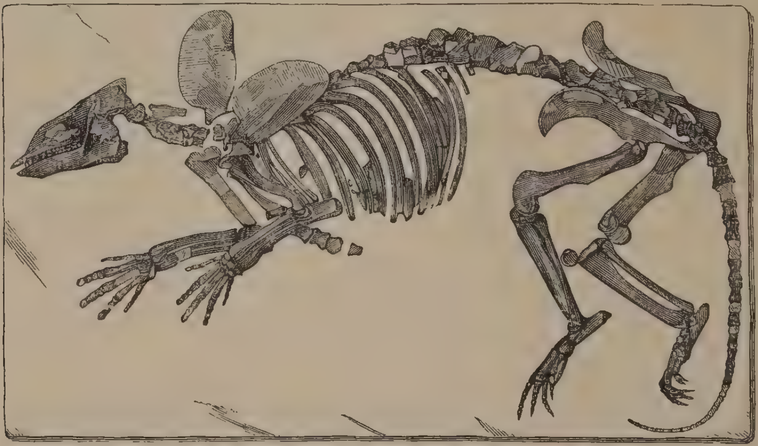

FIG. 918.—An almost perfect Skeleton of a Phenacodus primævus (after Cope).

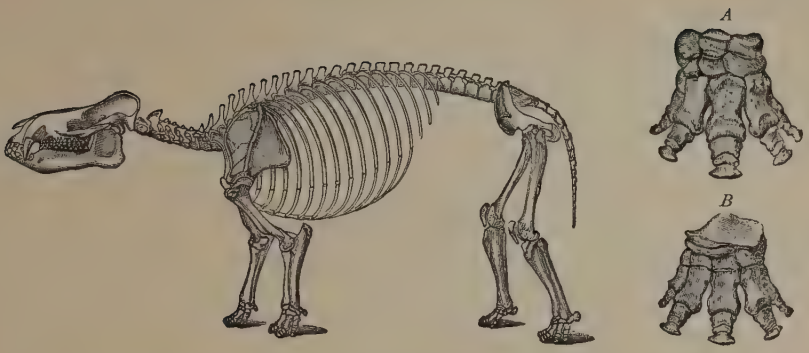

Fig. 919.—Coryphodon hamatus restored (after Marsh), × $\frac{1}{24}$: *A*, Hind-foot; *B*, Fore-foot, × $\frac{1}{8}$.

regarded as the ancestor of the Ungulates, or hoofed animals, but with almost equal right may be claimed as the ancestor of other orders. It was plantigrade, five-toed, each toe provided with a *flat nail*, which was neither claw nor hoof, but between the two. It had bunodont molars, a full complement of unmodified teeth without diastema. It was, therefore, probably omnivorous in habit. Cope has described nine species partly from this horizon and partly from the previous. They were about the size of a sheep, or perhaps a little larger. The *Coryphodon* was a genus of large animals, of very generalized structure, uniting the characters of the more generalized Ungulates, such as Tapirs, with those of the more generalized Carnivores, such as Bears. They were five-toed Ungulates with full number of unmodified foot-bones, and a tread somewhat like that of an Elephant. Eight or ten species of Coryphodontidæ have been described, varying in size from that of a Tapir to that of an ox or larger (Fig. 919).

In the same beds are found the remains of what is believed to be the earliest progenitors of the *horse family*, viz., the *Eohippus* (dawn-horse). This was a small animal about the size of the fox, with three hoofed toes on the hind-feet, and four functional toes, a fifth metacarpal, and a corresponding rudimentary fifth toe on the fore-feet (Fig. 920).

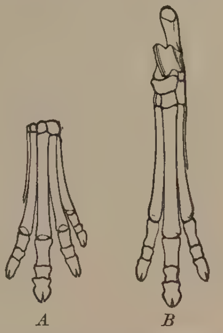

Fig. 920.—Feet of Eohippus: *A*. Fore-foot; *B*, Hind-foot, × $\frac{2}{3}$ (after Marsh).

As already said, generalized Carnivores, Insectivores, and lemurine monkeys, *Pro-Simiæ*, are found in this and the previous horizon.

7. **Green River Basin—Bridger Beds—Middle Eocene.**—From this wonderful fresh-water deposit there have been described by Marsh, Cope, and Leidy, 150 species of vertebrates, of which the larger number are mammals. This shows a marvelous abundance of mammalian life

in this early Tertiary time. The most numerous of these are tapir-like animals, such as *Hyrachyus*, *Limnohyus* (*Palæosyops*—Fig. 923), etc.; but the most formidable are the *Dinocerata*, an order established by Marsh and including the genera *Dinoceras* (Marsh), *Uintatherium* (Leidy), and *Tinoceras* (Marsh), or *Loxolophodon* (Cope). The remains of thirty species and more than one hundred and fifty distinct individuals of this order have been obtained from the Middle Eocene of Wyoming and deposited in the Museum of Yale College, where they have been carefully studied.

The type genus of this order is the Dinoceras. Almost every bone in the skeleton of this animal is now known. Although elephantine in size, there is no evidence in the skull of the existence of a proboscis; the proportions of the neck and fore-limbs, furthermore, show that its presence was unnecessary. Three pairs of horns are indicated by the projecting cores (Fig. 921), one pair of which stood far in front

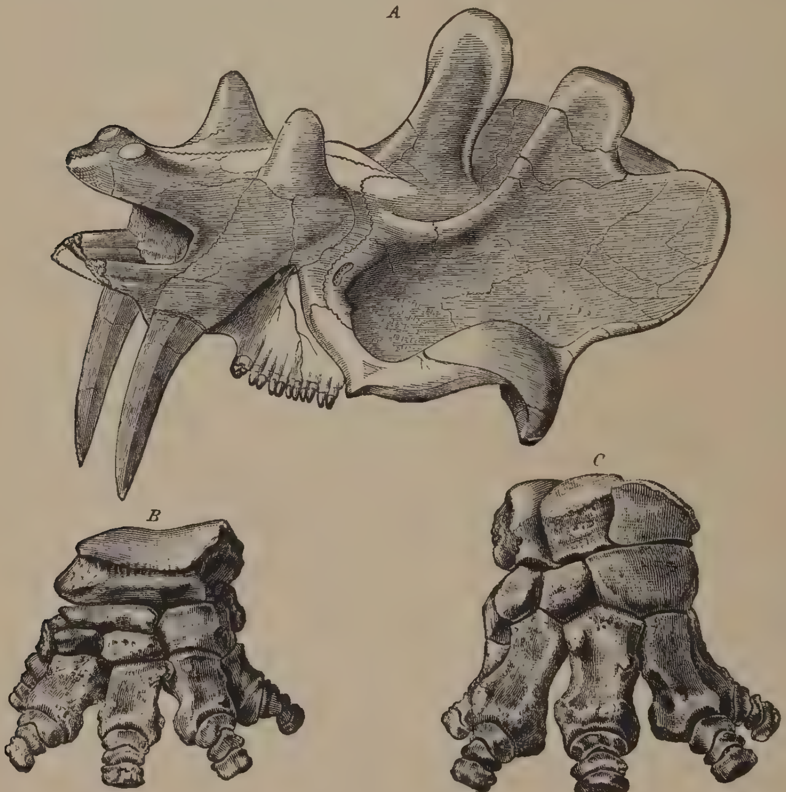

FIG. 921.—Dinoceras mirabile, × $\frac{1}{8}$ (after Marsh): *A*, Skull; *B*, Hind-foot, × $\frac{1}{5}$; *C*, Fore-foot, × $\frac{1}{6}$.

on the nasal bones, another on the maxillary bones immediately above the canines, and a third and much larger pair farther back on the parietal bones. This last pair were sheathed with a thickened integument, which may have developed into true horn, as in the Prong-horned Antelope. The three pairs of elevations are present in both sexes, but proportionately smaller in the females. In addition to these formidable weapons, both sexes were provided with canine tusks, those of the males being very powerful, in some cases seven or eight inches in length.

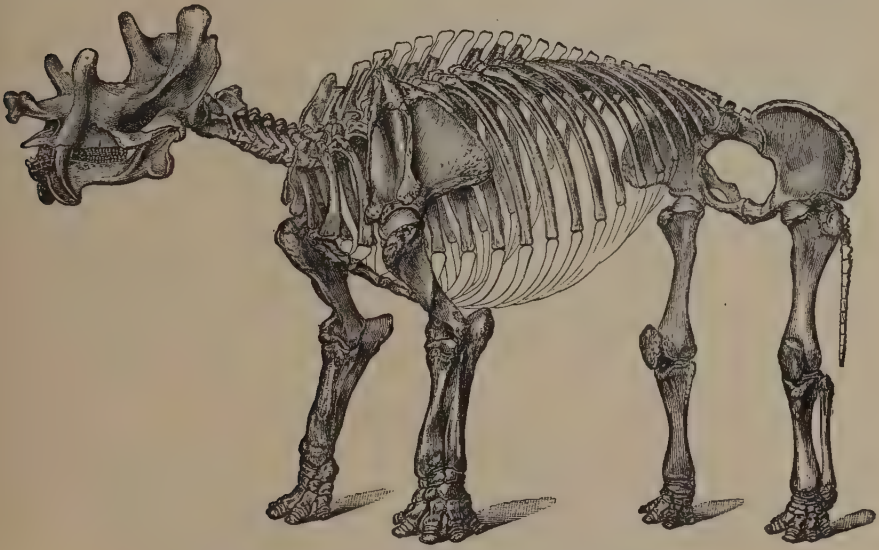

Fig. 922.—Restoration of Tinoceras ingens, × $\frac{1}{30}$ (after Marsh).

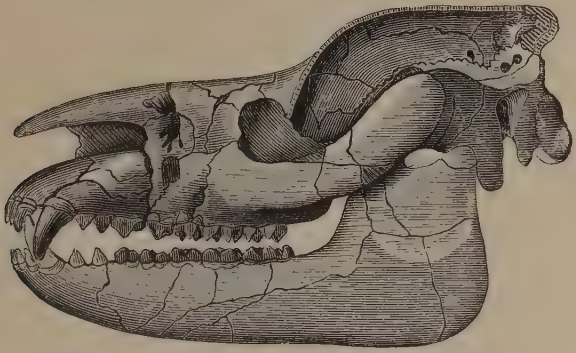

Fig. 923.—Limnohyus (Palæosyops) (after Leidy).

The largest, most specialized, and latest of the Dinocerata was the huge monster Tinoceras. The head of this animal was four feet in length, and the horn-cores much longer than in Dinoceras. Fig. 922 is a restoration by Marsh of this magnificent animal.

The animals of this entire order seem to have been quite abundant for a short time during the latter part of the Middle Eocene. They then became extinct, leaving apparently no successors, though possibly the Elephant tribe of to-day may be their greatly modified descendants. Their feet were provided each with five toes (Fig. 921), and the brain was proportionally smaller than in any other land mammal.

Another extraordinary group of animals discovered by Marsh in the Eocene beds has been placed by him in a new order called *Tillodontia* (Fig. 924). These animals combine the head and claws of a bear with the incisors of a Rodent and the general characters of Ungulates. The order must be regarded, therefore, as a remarkable generalized type.

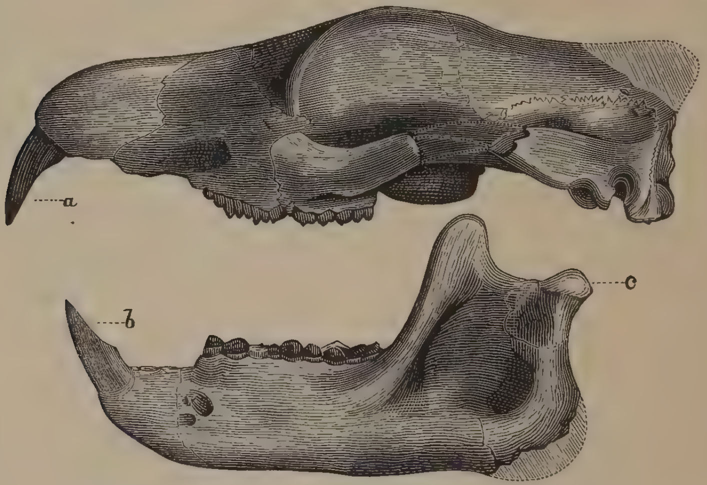

FIG. 924.—EOCENE MAMMAL: Skull of Tillotherium (after Marsh).

We have seen the earliest in the line of descent of the horse family —*Eohippus*—in the Lower Eocene Wahsatch beds. In the Middle Eocene Bridger beds we find the next in the series—the *Orohippus* (mountain-horse). This was of similar size; but already the fifth metacarp and rudimentary toe are gone, and there were now three hoofed toes on the hind-feet and four functional toes on the fore-feet.

Although the Herbivores predominated, there were many mammals belonging to other orders. For example, there were species allied to the Cat, Wolf, and Fox; also Bats, Squirrels, Moles, and Marsupials; also many Monkeys allied to the Lemurs, Marmosets, etc., but more generalized than any living Lemur. In Fig. 925 we give a restoration by Wortman of an Eocene carnivore—*Patriofelis*—of very generalized structure and plantigrade feet. It may be regarded as the generalized ancestor of the Cats.

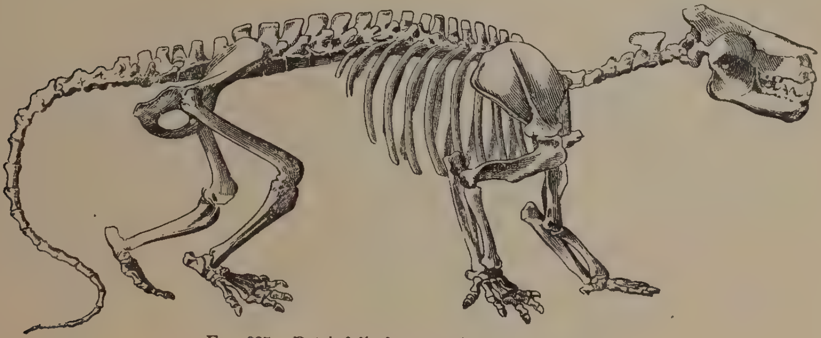

Fig 925.—Patriofelis ferox, × $\frac{1}{18}$ (after Wortman).

8. **Mauvaises Terres of Nebraska—White River Basin—Miocene.**—From this, the earliest discovered of the Tertiary basins of the West (see Fig. 851, p. 522), have been collected by Hayden and described by Leidy more than 40 species of mammals, of which 25 are Ungulates, 8 Carnivores, and the remainder mostly Rodents. Many other species have been discovered in the same locality since that time. All the species, nearly all the genera, and many even of the families, are entirely different from those found in the preceding epoch, and much more modern. Although the tapir-like animals still prevail, species of the deer, the camel, the horse, and the dog families are added. This is seen in the following schedule:

Carnivores	Hyena, allies.	Dog family.
	Wolf, "	
	Tiger, "	Cat "
	Panther, "	
Ungulates	Rhinoceros family.	
	Brontotheridæ.	
	Tapir-like animals.	
	Deer family.	
	Camel "	
	Horse "	
	Rodents.	
	Turtles.	

The most extraordinary animals of this time were the Brontotheridæ. This family, according to Marsh, included the Brontotherium, the Menodus (Titanotherium), the Brontops, and several other genera.

They were of elephantine size, with singular, saddle-shaped head like a Rhinoceros, and with at least one pair of large horns on the maxillaries.

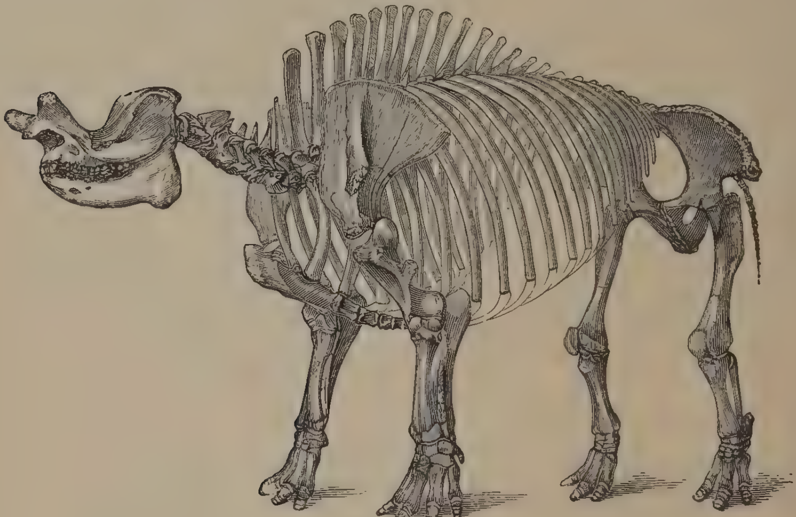

FIG. 926.—Brontops, restored by Marsh, × $\frac{1}{36}$.

These are sometimes enormously elongated. Fig. 926 is a restoration of Brontops by Marsh. They are a very distinct family, characteristic of the Miocene, but their nearest living allies are the Rhinoceros and the Tapirs. Like the latter, they had three hoofed toes on the

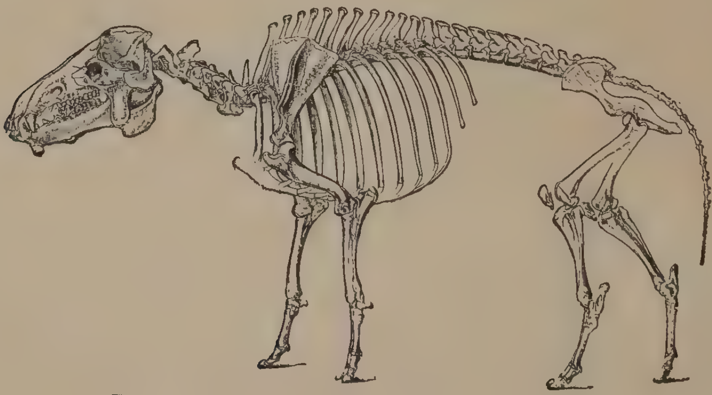

FIG. 927.—Entelodon crassus (after Marsh), × $\frac{1}{24}$. Miocene.

hind-feet and four on the fore-feet. In Fig. 927 we give a restoration of another very remarkable animal of this period.

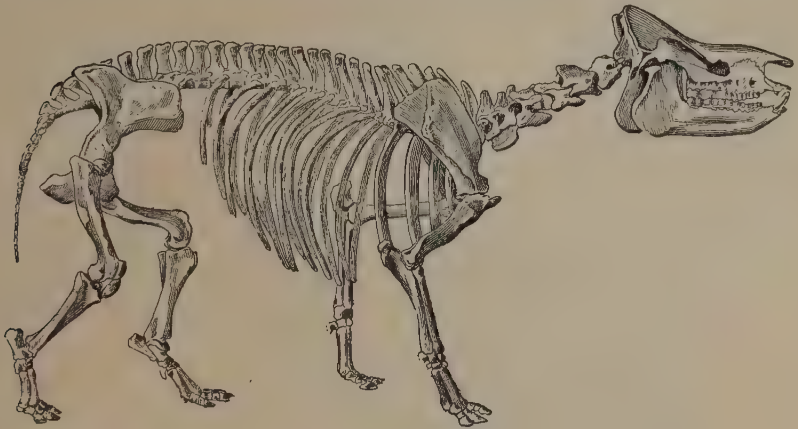

FIG. 928.—Aceratherium tridactylum, × $\frac{1}{18}$ (after Osborn and Wortman).

The Rhinoceros family commenced here, and were abundant in America. A restoration of an early generalized form is given in Fig. 928.

Several of the Horse family are found in the Miocene, especially the *Mesohippus* and the *Miohippus*. These had lost the fourth toe on the fore-feet possessed by the *Orohippus*, and therefore had *three toes on all the feet*. They may be regarded as the first of the *true* horse family,

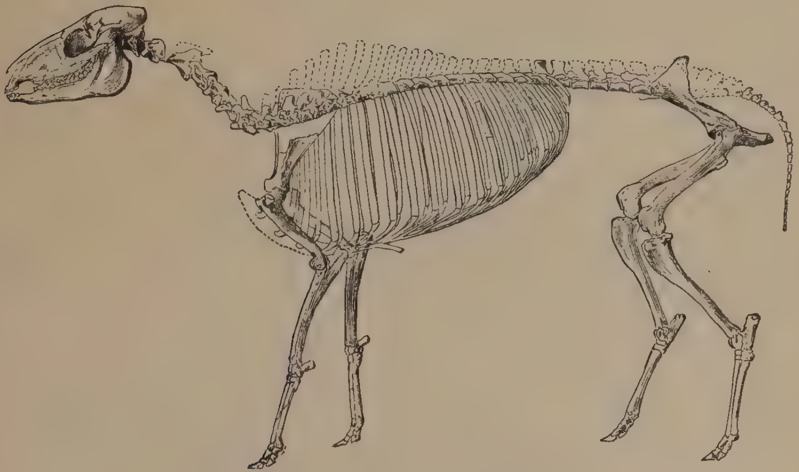

FIG. 929.—Mesohippus Bairdii, × $\frac{1}{10}$ (restored by Scott).

Equidæ. These three-toed horses were about the size of a sheep. In Fig. 929 we give a restoration of the Mesohippus.

The *Oreodon* was another remarkable animal of generalized structure, intermediate between the Hog and the Deer, which at this time inhabited in great numbers the whole continent from Nebraska to Oregon. Thirty-five species of Oreodontidæ are known, although not all from this horizon. The head of one is given below (Fig. 930).

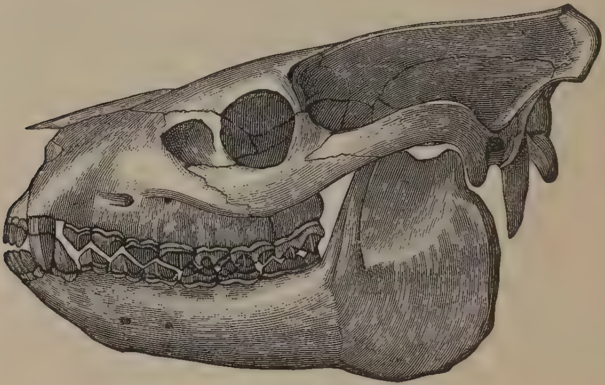

FIG. 930.—Oreodon Culbertsoni (after Gaudry).

Another most extraordinary and very generalized Artiodactyl, found in both the White River and the John Day basins, is the Agriochærus, a restoration of which is given in Fig. 931. The singular combination of claw and hoof and the plantigrade tread, especially of the hind-feet, will be noted.

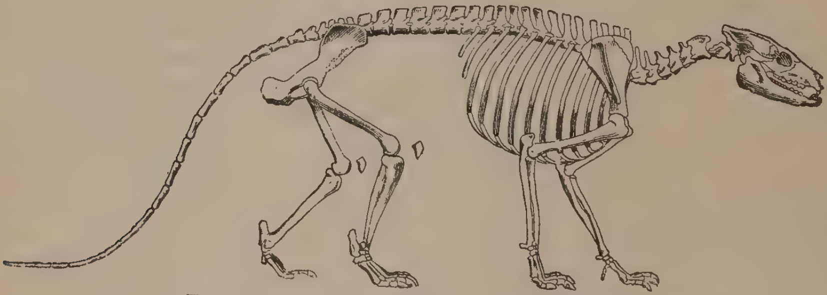

FIG. 931.—Agriochærus latefrons, × $\frac{1}{18}$ (after Wortman).

The great abundance of the Dog family in the Miocene of America and their comparative scarcity in the Old World, and also the much greater abundance of Rhinoceroses, Horses, and Camels, indicate that all those families probably originated here. In Fig. 932 we give a restoration of the Pœbrothere, an early form of Camel, and in Fig. 933 a most remarkable and very generalized form of the Dog family.

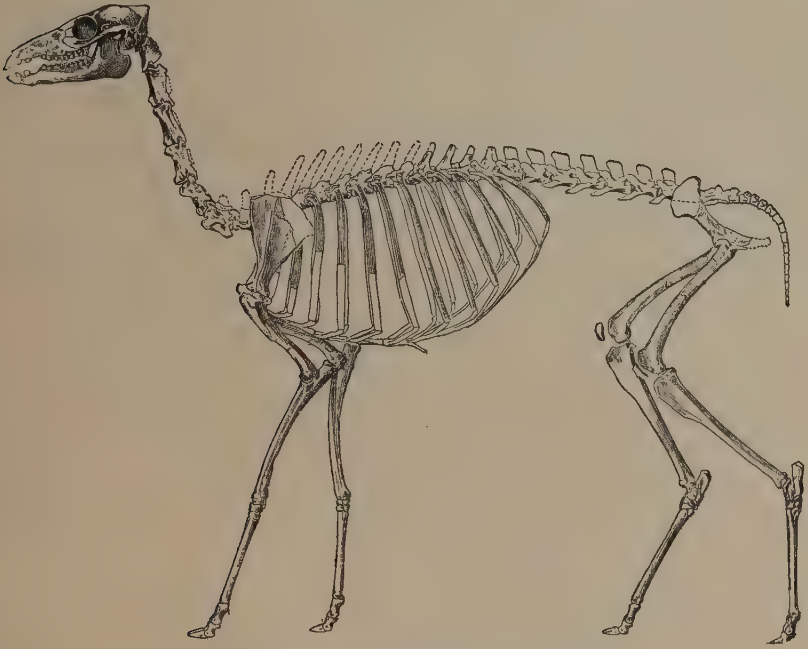

FIG. 932.—Pœbrotherium labiatum × ⅛ (after Scott).

Among Carnivores, besides many species of the Cat family, Cope has described ten species of the Dog family. The saber-toothed Tiger,

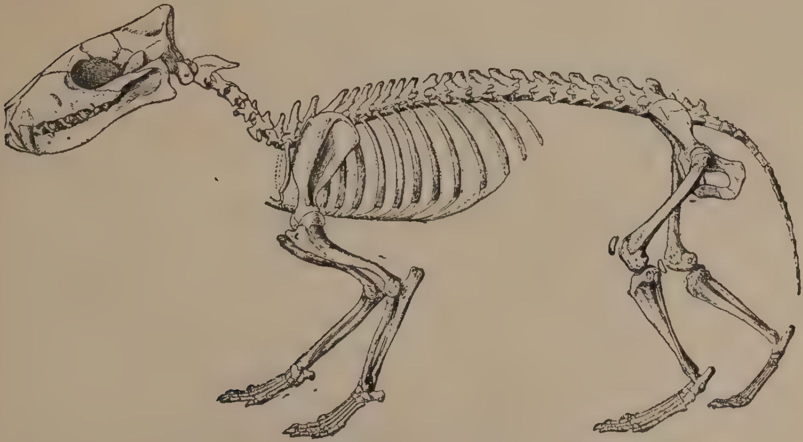

FIG. 933.—Hyænodon cruentus, × ⅛ (restored by Scott).

a most remarkable family, which culminated later in the Quaternary, seems to have made its first appearance here. In Fig. 934 we give an early Miocene form of this family of Cats.

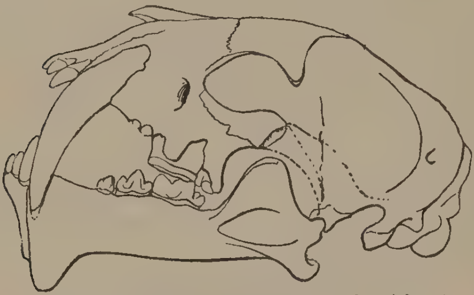

Fig. 934.—Hoplophoneus robustus, × $\frac{3}{8}$ (after Adams).

It is well to note that in the Miocene, for the first time, *existing families of mammals began to appear.* We have here the families of the dog, the cat, the deer, the camel, the horse, and the rhinoceros. It is well to note also that the American Continent, as shown by the uniqueness of its mammalian fauna, was still largely, if not completely isolated.

9. **Mauvaises Terres—Niobrara Basin—Loup Fork Beds—Pliocene.**—In nearly the same locality overlying the last, but extending farther south, occur lake-deposits of the Pliocene times, full of mammalian remains, but again wholly different in species. Among Ungulates there was a Rhinoceros, as big as the Indian species; an Elephant (*E. Americanus*), the same which lived in the Quaternary, bigger than any now living; a Mastodon, but smaller than the great Mastodon of the Quaternary; a large number of the horse family and several of the camel family, besides many other families of Ungulates, Carnivores, Rodents, etc. Both the horse and the camel family were more numerously represented at that time in America than in the Eastern Continent. In fact, it is not at all improbable that they originated here, and emigrated to the other continent. From the presence of Elephants, Mastodons, Rhinoceros, Camels, and Horses on both continents, we conclude *that the two continents were probably connected* in Pliocene times.

Rhinoceros.
Elephant.
Mastodon.
Several of the Camel family.
Many of the Horse "
Oreodon.
Deer.
Fox.
Wolf.
Tiger.
Beaver.
Porcupine.

Among the horse family found here, the most interesting, as showing the gradual approach toward the modern horse, are the *Protohippus* and the *Pliohippus.* These were larger than the Miocene horses, being about the size of the ass. The former was three-toed, but the two side-toes were smaller and shorter and scarcely functional, unless on marshy ground; the latter had already lost the side-toes, and was almost but not quite a perfect horse.

We see here for the first time *existing genera. Elephas*, *Canis*, and in the higher beds *Equus* begin to appear, but not yet existing *species*, for these do not appear until the Quaternary. The successive appearance and increasing percentage of existing orders, families, genera, and species of mammals, is shown in a very general way in the accompanying diagram.

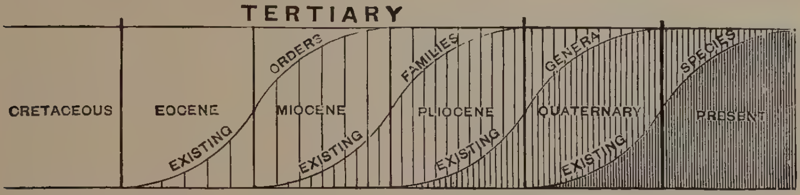

FIG. 935.—The Successive Appearance and Increasing Percentage of Existing Orders, Families, Genera, and Species of Mammals.

Some General Observations on the Tertiary Mammalian Fauna.—1. *Size of Brain.*—Lartet has shown that the *brain-cavity* of some of the Tertiary animals is decidedly *smaller* relatively than that of their living congeners. Marsh has, moreover, traced a gradual increase in the relative size of the brain from the earliest Eocene to the present time. The brain of the *Coryphodon*, Lower Eocene, is not only extremely small in proportion to the size of the animal, but the higher portion of the brain—the cerebral lobes—is very small in proportion to the cerebellum. The brain of the Middle Eocene Dinoceras is only about one eighth the size of that of a living Rhinoceros of equal bulk. The brain of the Miocene Brontothere is larger than that of the Eocene Dinoceras, but much smaller than that of the Pliocene Mastodon of nearly the same size, and proportionally much smaller than that of the horse (Figs. 936, 937, and 938). Through the whole line of ancestry of the horse the gradually-increasing size of the brain may be traced step by step. As already seen, page 510, the same was true of early birds and reptiles. There has been a gradual increase in brain-power, and therefore in nerve and muscular energy, in all classes.

2. *Genesis of Existing Orders.*—We have seen that the main branches of the Mammalian class if traced backward, approach one another very closely in the Early Tertiary; and if we could trace them still further back, they would unite in the Cretaceous in a common stem or *primal mammal.* This was doubtless a plantigrade, five-toed, bunodont, omnivorous animal. From this common stem the Carnivores and the Ungulates—to take only the two most widely-contrasted types—diverged more and more in all their characters—the one becoming more and more adapted to flesh-eating, the other to herb-eating; the one for seizing, the other for escaping—until the present extreme types were attained.

3. *Genesis of Existing Families.*—Not only did these two main branches separate more and more, but each of them branched again to

form existing families. To illustrate this we take the order of Ungulates as the best known.

Cuvier divided all Ungulates into two orders, viz., *Pachyderms* and *Ruminants*. The Pachyderms are a heterogeneous order, but the Ru-

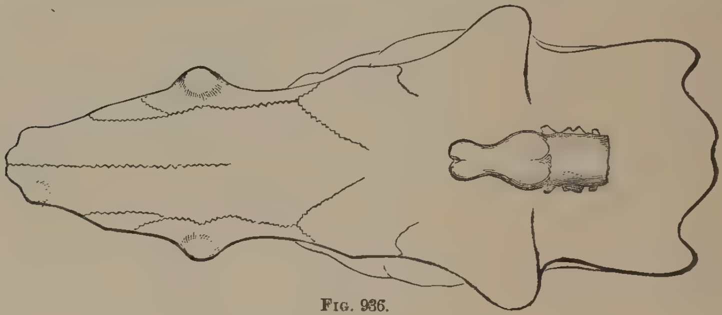

FIG. 936.

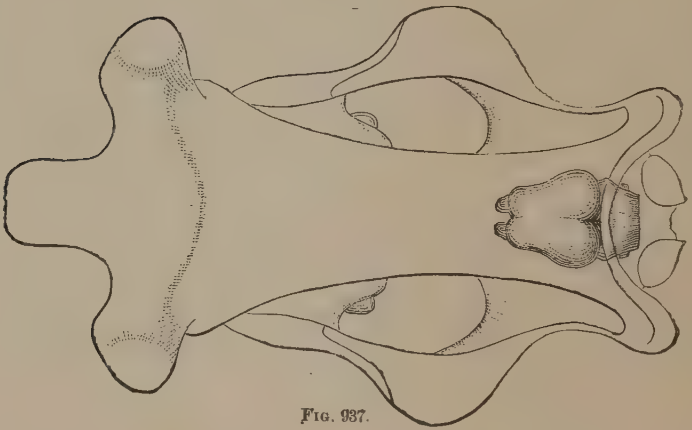

FIG. 937.

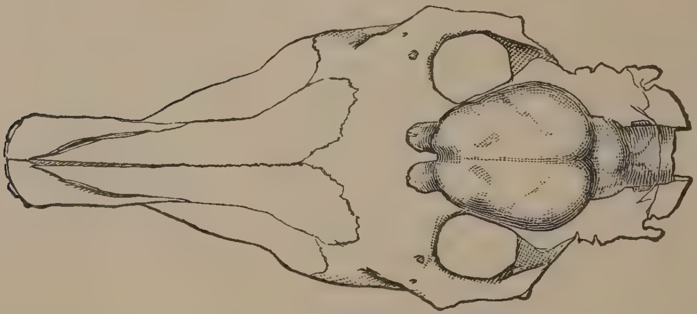

FIG. 938.

FIGS. 936-938.—BRAINS OF DINOCERAS, BRONTOTHERIUM, AND HORSE, COMPARED (after Marsh): 936. Dinoceras, Skull and Brain, × $\frac{1}{8}$. 937. Brontotherium, Skull and Brain, × $\frac{1}{12}$. 938. Horse, Skull and Brain, × $\frac{1}{3}$.

minants have been regarded as one of the most distinct of all mammalian orders. Their horns in pairs, their hoofs in pairs, absence of upper front-teeth, complex stomachs, and the habit of rumination, differentiated them widely from all other animals. But Prof. Owen showed that this distinction, so clear in zoölogy, was untenable in paleontology. He found, in studying extinct Ungulates, that another distinction, viz., foot-structure, was more fundamental and persistent. He therefore divided all Ungulates into *Perissodactyls* (odd-toed) and *Artiodactyls* (even-toed). A Perissodactyl may have five toes, as in the Coryphodon; or three toes, as in the Palæothere, the Rhinoceros, and the Tapir; or one toe, as in the Horse. The Artiodactyls always have their toes in pairs: there may be only two toes, as in Anoplothere and in Ruminants; or four, as in the Hog and the Hippopotamus. The Elephant, Mastodon, etc., may be regarded as a distinct order, *Proboscidians.* It is probable therefore, that Ungulates very early divided into three branches.

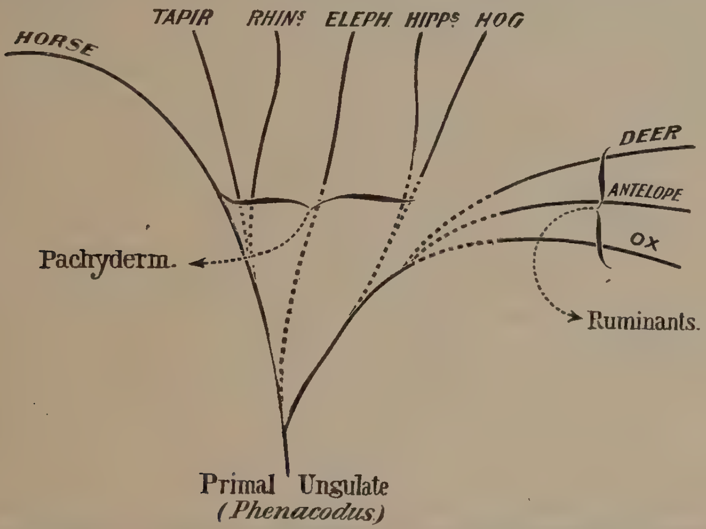

FIG. 939.—Diagram illustrating the Differentiation of the Different Families of Ungulates.

Now in the Earliest Tertiary the sub-orders Artiodactyls and Perissodactyls and Proboscidians were united in a common ancestor or *primal Ungulate*, from which they afterward separated. The Phenacodus of Cope (Fig. 918, p. 550) is perhaps such a primal Ungulate. Each of the primary branches then divided and again divided, until the extreme branch in one direction became the Horse, and the extreme branch in the other direction the Ox. In the tree above we have attempted, in a general way, to represent the differentiation of the several orders of Ungulates. The Cuvierian orders, *Pachyderms*, and *Ruminants*, are indicated by a vinculum. It is seen at a glance why, in studying living animals alone, the Ruminants seem so distinct.

Genesis of the Horse.—In conclusion, it will be interesting and instructive to run out one of these branches and show in more detail the genesis of one of the extreme forms. For this purpose we select the Horse, because it has been somewhat accurately traced by Huxley and by Marsh. About thirty-five or forty species of this family, ranging from the earliest Eocene to the Quaternary, are known in the United States. The steps of evolution may therefore be clearly traced.

In the lower part of the Eocene basin (*Coryphodon beds*) of Green River is found the earliest known animal in the direct line of descent of the horse family, viz., the *Eohippus* of Marsh. This animal had three toes on the hind-foot and four perfect, serviceable toes on the fore-foot; but, in addition, on the fore-foot an imperfect fifth metacarpal (splint), and possibly a corresponding rudimentary fifth toe (the thumb), like a dew-claw. Also, the two bones of the leg and forearm were yet *entirely distinct.* This animal was *no larger than a fox.* Next, in the *Middle Eocene* (Bridger beds), came the *Orohippus* of Marsh, an animal of similar size, and having similar structure, except that the rudimentary thumb or dew-claw is dropped, leaving only four toes on the fore-foot. Next came, in the *Lower Miocene*, the *Mesohippus*, in which the fourth toe has become a rudimentary and useless splint. Next came, still in the *Miocene*, the *Miohippus* of the United States and nearly-allied *Anchithere* of Europe, more horse-like than the preceding. The rudimentary fourth splint is now almost gone, and the middle hoof has become larger; nevertheless, the two side-hoofs are still serviceable. The two bones of the leg have also become united, though still quite distinct. This animal was about *the size of a sheep.* Next came, in the *Upper Miocene* and *Lower Pliocene*, the *Protohippus* of the United States and allied *Hipparion* of Europe, an animal still more horse-like than the preceding, both in structure and size. Every remnant of the fourth splint is now gone; the middle hoof has become still larger, and the two side-hoofs smaller and shorter, and no longer serviceable, except in marshy ground. It was about the *size of the ass.* Next came, in the *Pliocene*, the *Pliohippus*, almost a complete horse. The hoofs are reduced to one, but the splints of the two side-toes remain to attest the line of descent. It differs from the true horse in the skull, shape of the hoof, the less length of the molars, and some other less important details. Last comes, in the *Quaternary*, the modern horse—*Equus*. The hoof becomes rounder, the splint-bones shorter, the molars longer, the second bone of the leg more rudimentary, and the evolutionary change is complete.

Similar gradual changes, becoming more and more horse-like, may be traced in the shape of the head and neck, and especially in the gradually-increasing length and complexity of structure of the grind-

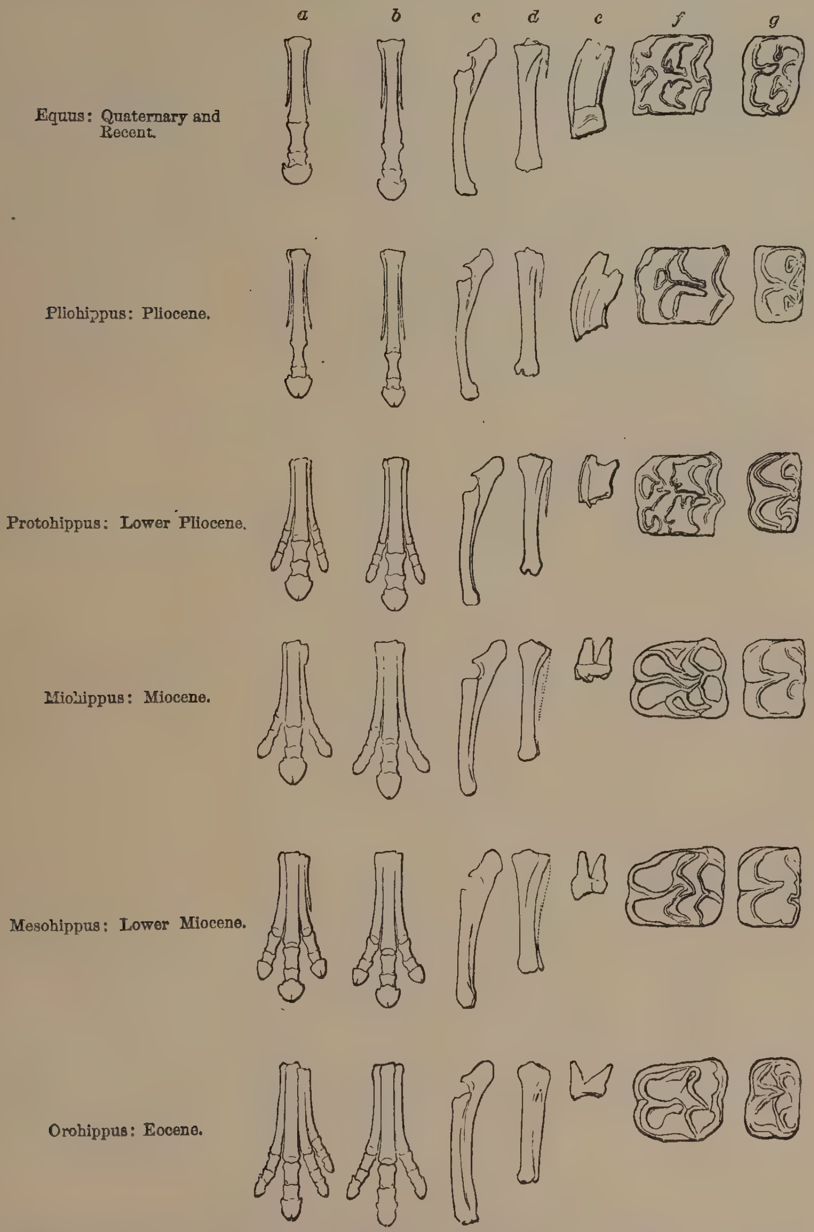
a
b
c
d
e
f
g
Equus: Quaternary and Recent.
Pliohippus: Pliocene.
Protohippus: Lower Pliocene.
Miohippus: Miocene.
Mesohippus: Lower Miocene.
Orohippus: Eocene.

Fig. 940.—Diagram illustrating Gradual Changes in the Horse Family. Throughout *a* is fore-foot; *b*, hind-foot; *c*, fore-arm; *d*, shank; *e*, molar on side view; *f* and *g*, grinding surface of upper and lower molars. (After Marsh.)

ing teeth. These changes are shown in Fig. 940, for which we are indebted to the kindness of Prof. Marsh. The Eohippus is not represented, but figures of its feet are given in Fig. 920, p. 551.

There can be no doubt that if we could trace the line of descent still further back we would find a perfect five-toed ancestor. From this normal number of five, the toes have been successively dropped, according to a regular law. In the *Perissodactyl* line first the thumb, No. 1, was dropped; then the little finger, No. 5; then the first and ring-fingers, Nos. 2 and 4, were shortened up more and more and finally disappeared, and only the middle finger, No. 3, remained in the modern horse. In the *Artiodactyl* line, after the dropping of No. 1, then Nos. 2 and 5 of the four-toed foot were shortened and gradually disappeared, and Nos. 3 and 4 remained in the ruminants.

In a similar way Cope has traced the line of descent of the camel from the Pantolestes of the Early Eocene, through the Poebrotherium (Fig. 932) of the Miocene, and the Procamelus of the Pliocene, to the modern camel.* Similarly also the modern deer, with its branching antlers, may be traced from the Lower Pliocene, where they had antlers of one or two points, through the Upper Pliocene, where the antlers are more complex, to the magnificent, many-branched antlers of the Quaternary and modern times.

From the earliest and most generalized types, therefore, to the present specialized types, the principal changes have been, first, from plantigrade to digitigrade; second, from short-footed digitigrade to long-footed digitigrade, i. e., *increasing elevation of the heel;* third, from digitigrade to unguligrade, i. e., rising on tips of the toes; fourth, from five toes to one toe in the Horse, or two toes in Ruminants; and, fifth, from simple omnivorous molars to the complex herbivorous millstones of the Horse and the Ox.

The change from plantigrade to digitigrade and from digitigrade to unguligrade, with increasing elevation of the heel, when taken in connection with increasing size of the brain, and therefore presumably with increasing brain-power, shows a gradual improvement of structure adapted for speed and activity, and a *pari-passu* increase of nervous and muscular energy, necessary to work the improved structure.

4. Not only does the mammalian fauna of the Miocene differ completely from that of the Eocene, which precedes, and from the Pliocene, which succeeds it, but there seem to have been at least three or four distinct Eocene and seven or eight distinct Miocene faunas. Thus there have been many complete changes in the mammalian fauna in Tertiary times.

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* American Naturalist, vol. xx, p. 611, 1886.

General Observations on the Tertiary Period.

We have already seen (p. 486) that during Cretaceous times a wide sea, occupying the position of the Western Plains and Plateau region, divided America into two Continents, an Eastern and a Western. We have also seen (p. 513) that at the end of the Cretaceous this sea was obliterated by continental upheaval, and the continent became one. During the Eocene, the eastern portion of the place formerly occupied by this sea was probably dry land, but in the Plateau region there were great fresh-water lakes, one north of the Uintah Mountains, Green River Basin, and one south of the same, and probably one in Oregon. There were possibly others yet unknown. At the end of the Eocene, there was a *rise* in the Plateau region, which drained the Eocene lakes, through the Colorado River, and a corresponding *depression* in the Plains region on the one side, and the Basin region on the other, not sufficient to form a sea again, but sufficient to form great Miocene lakes there. During the Miocene, the bared bottoms of the Eocene lakes were subject to prodigious erosion, and much of the general erosion of the Plateau region occurred at that time. At the end of the Miocene occurred the greatest event of the Tertiary period, one of the greatest in the history of the American Continent. At that time the sea-bottom off the then Pacific coast was crushed together into the most complicated folds (p. 270), and swollen up into the *Coast Chain*, and at the same time fissures were formed in the Cascade Range, with the outpouring of the great lava-flood of the Northwest, already spoken of (pp. 218, 273). Coincidently with this there was a further *letting down* of the region of the Plains and of the Basin, and a consequent extension of the Pliocene lakes in these regions, attended probably with a further rise of the Plateau region. During the Pliocene, the greater part of the cañon-cutting of the Plateau region, and nearly all the great lava-flows of the West, took place. At the end of the Tertiary, these Pliocene lakes were in their turn obliterated by the further upheaval of the continent, which inaugurated the Quaternary. Coincident with this general uplift, mountain-making by crust-block tilting occurred on a grand scale. The Sierra, the Wahsatch, and the Basin Ranges assumed their present form and height (p. 276), and the great north and south fault-cliffs of the Plateau region were mainly formed. At the same time there occurred another elevation of the Coast Range, and a folding of its Pliocene strata with outpouring of lavas. And last of all the final sculpturing of both Sierra and Coast Ranges began, and all the grand cañons of the Sierra and the inner gorge of the Colorado cañon were formed since that time.

While this was going on in the *western* portion of the continent, on the southeastern and southern border the continent gained, by gradual rise, nearly all the area shaded as Tertiary on map (p. 524). In this direction the continent was finished with the exception of a *large portion of Florida* and the *sea-islands* and *alluvial flats** about the shores of the Southern Atlantic and Gulf States. These belong to a still later period.

Thus we see that from the end of the Cretaceous to the end of the Tertiary there was a gradual upheaval of the whole western half of the continent, by which the axis, or lowest line, of the great interior continental basin was transferred more and more eastward to its present position, the Mississippi River. Probably correlative with this upheaval of the western half of the continent was the down-sinking of the mid-Pacific bottom, indicated by coral-reefs (p. 160). Also as a consequence of the same upheaval the erosive power of the rivers was greatly increased, and thus were formed those deep cañons in the regions (New Mexico, Colorado, and Arizona) where the elevation was greatest. Thus the *down-sinking* of the mid-Pacific bottom, the *bodily upheaval* of the Pacific side of the continent, and the *down-cutting* of the river-channels into those wonderful cañons, are closely connected with each other..

SECTION 2.—QUATERNARY PERIOD.

Characteristics.—The chief characteristic of the Quaternary is that it is a period of great and widely extended *oscillations* of the earth's crust in *high-latitude* regions, attended *with great changes of climate.* During this period the class of *mammals* seem to have *culminated.* During this period also *man* seems to have *appeared* on the scene. We do not call it the age of Man, however, because he had not yet established his reign. His appearance here is rather in accordance with the law of *anticipation* (p. 291). As already stated, the invertebrate fauna was almost identical with that still living, but the mammalian fauna was almost wholly peculiar, differing both from the Tertiary which preceded and from the present which followed it.

Subdivisions.—The Quaternary period is divided into two epochs, viz.: I. *Glacial;* II. *Champlain.* These epochs are characterized by the *attitude* of the *land surface* and the *character of the climate.* The *Glacial* epoch is characterized by an *upward* movement of the crust in high-latitude regions, until the continents in those regions stood 1,000 to 3,000 feet above their present height. Large portions of these regions seem to have been sheeted with ice, and an arctic rigor of climate extended far into now temperate regions.

The *Champlain* epoch, on the contrary, is characterized by a *down-*

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* In some places about the shores of the Gulf, for reasons which will be explained hereafter, the Quaternary deposits are considerably elevated above the sea-level (p. 581).

ward motion of land-surfaces in the same region until the sea stood relatively 500 to 1,000 feet above its present level, covering, of course, much that is now land-surface. It was, therefore, a period of *inland* seas. Coincident with this sinking was a *moderation* of climate, and a *melting of the ice.* It was, therefore, also a period of *great lakes* and *flooded rivers.* Over the inland seas and great lakes, masses of *ice,* loosened from the ice-sheet on their northern borders, *floated.* It was, therefore, also a period of *icebergs.* From this subsided condition the land rose again gradually to its present condition. This restoration is sometimes called the Terrace epoch.

Although we call these divisions *epochs*, yet we must not suppose that they are equal in length to the epochs of earlier times. As we approach the present time, and the number and interest of events increase, our divisions of time become shorter and shorter.

It is so difficult to separate these epochs sharply from each other in all countries, and to synchronize them, that it seems best to treat of the whole Quaternary period, taking up the epochs successively—first in Eastern North America, as the type or term of comparison, then of the same on the Pacific coast, and last of the same in Europe.

Quaternary Period in Eastern North America.

I. Glacial Epoch.

The Materials — Drift.—Strewed all over the northern part of North America, over hill and dale, over mountain and valley, covering alike nearly all the country rock, Archæan, Palæozoic, Mesozoic, and Tertiary, to a depth of 30 to 300 feet, and thus largely concealing them from view, is found a *peculiar* surface soil or deposit. It consists of a heterogeneous mixture of clay, sand, gravel, pebbles, subangular stones of all sizes, unsorted, unstratified, unfossiliferous—of all sorts of materials on all sorts of bed rock, wholly unrelated to the underlying rock and therefore universally shifted. The lowest part, lying in immediate contact with the subjacent country rock, is often a stiff clay inclosing subangular stones—i. e., rock-fragments with the corners and edges rubbed off. This we will call the "*Stony clay*" or "*Bowlder clay*" or "*Till.*" It is precisely like the ground-moraine of a glacier (p. 55). Over this is often found in places a looser material with *angular* stones, like the top moraine of glaciers. Lying on the surface of this drift-soil are found many bowlders of all sizes, often of huge dimensions, sometimes even 100 tons or more. The imbedded subangular stones are usually *marked with parallel scratches* (Fig. 941), and the large surface-bowlders are usually *angular and unscratched.* The depth of this material is greatest in the valleys and least on hill and mountain tops.

It is difficult, nay, impossible, to give a description of this peculiar deposit, which will apply in all cases. Sometimes scattered about irregularly through the unstratified mass are portions which are roughly and *irregularly stratified*, the laminæ being often contorted in the most fantastic way (Figs. 942–944). Sometimes the true *stony clay* or *till* is covered with a more regularly *stratified* material, consisting of sand and gravel, apparently subsequently deposited from water. This is particularly the case in the basin of the Mississippi, as, e. g., in Ohio, Illinois, and Iowa. It is probable, however, that much of this belongs to the next epoch, Champlain. Sometimes irregular mound-like deposits are left in the retreat of the ice. These are called *kames*, *drumlins*, *osârs*, etc. *Kames* are mound-like deposits of *stratified* materials. When elongated and meandering they are called *osârs*. *Drumlins* are lens-like masses of till elongated in the direction of glacial motion. The conditions

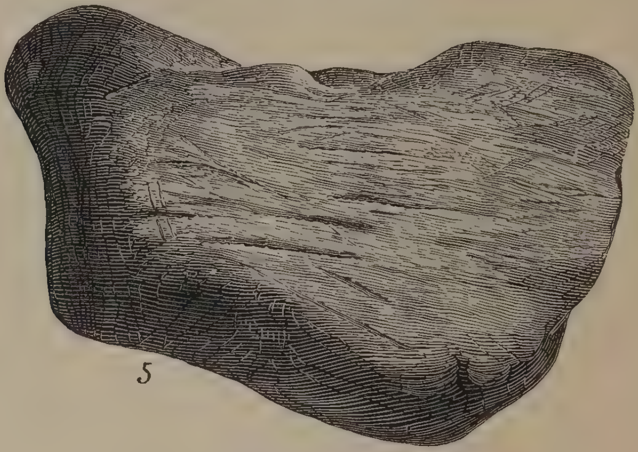

Fig. 941.—Subangular Stone (after Geikie).

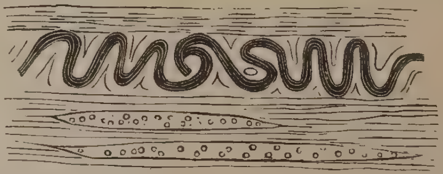

Fig. 942.—Section on Rush Creek, near Mono Lake, California.

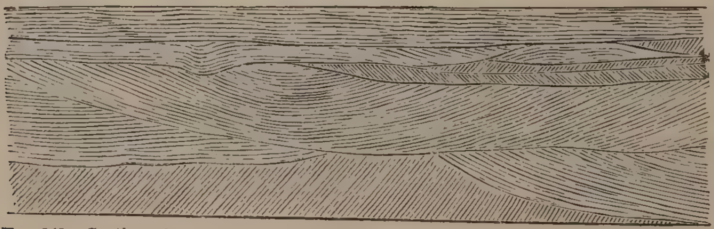

Fig. 943.—Section of Orange Sand or La Fayette Formation, Mississippi (after Hilgard).

under which these are formed are imperfectly understood, but it is believed that kames and osârs are deposits from super-glacial or subglacial streams, while drumlins are masses of ground-moraines rounded into turtle-back forms by glacial erosion.

We have said that the deposit is peculiar. Nothing resembling it is found anywhere in tropical or *low-latitude countries*. In the Southern Atlantic States, for instance, the soil is mostly either the insoluble residue of rocks decomposed *in situ*, or else consists of neatly stratified sands and clays.

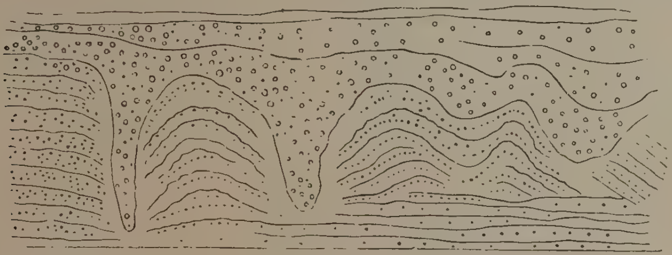

FIG. 944.—Section of Orange Sand or La Fayette Formation, Mississippi (after Hilgard).

Drift-material is *not* usually represented on geological maps, since it covers all kinds of country rock; or else the colors representing the various kinds and ages of country rock are simply *dotted* to indicate the presence of this surface-material. In sections, of course, it is easily represented, as in Fig. 945.

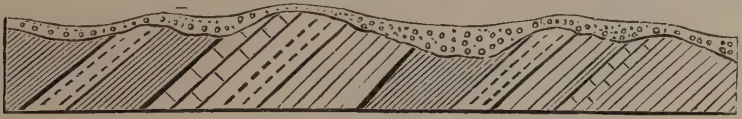

FIG. 945.—Outcropping—Eroded Country Rock overlaid by Drift.

The Bowlders.—The most casual examination of the great bowlders is sufficient in many cases to show that they do not belong to the country where they now lie, for they are of entirely different material from the country rock. For example, blocks of granite are found where there is no granite within many miles, blocks of sandstone on a country rock of limestone, or *vice versa*. In many cases it is easy to find the parent ledge from which these great fragments were torn, and thus to trace the *direction* of their transportation. From many observations of this kind it has been determined that in New England the bowlders have come usually from the *northwest*, in Ohio from the *north*, and in Iowa from the *northeast*. In other words, from the highlands of Canada and a ridge running thence northwestward (Archæan area), the general direction of travel has been southeast, south, and southwest. North of the Archæan areas the travel was probably in some cases even northward. The distance carried may be only a few miles, or may be ten, fifty, one hundred, or even several hundred miles. In many cases they must have been carried across valleys 1,000 or 2,000 feet deep, and lodged high up on the mountain beyond. In many portions of New England and about Lake Superior the number of fragments, small and great, is so large as seriously to encumber the soil. Not only the large bowlders, however, but the whole mass of the material we have been describing, seem to have been shifted to a greater or less extent. It is for this reason that the material has been called *Drift*.

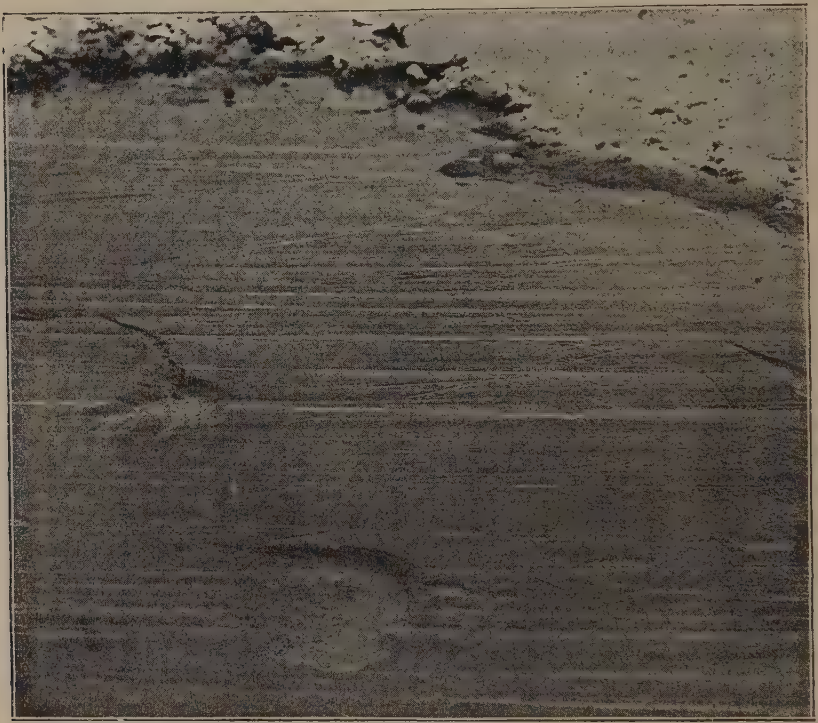

Fig. 946.—Bed-rock scored with glacial marks, near Amherst, Ohio. (From a photograph by Chamberlin.)

Surface-Rock underlying Drift.—On removing the drift-covering the underlying rock is everywhere *polished* and *planed* and *scored* with parallel lines (Fig. 946) deeply fluted (Fig. 947), and *moutonné*, precisely like rocks over which a glacier has passed (see Fig. 43, p. 56). We will, therefore, call this surface-appearance "*glaciation*." Examinations of the scorings show that they often pass straight up inclines for considerable distances, i. e., up one side of a hill, over the top, and down the other side. Their direction is uninfluenced by smaller inequalities of surface, though they are thus influenced by the *great valleys* and *mountain-ridges*.

The general direction of the scorings corresponds with that of transportation of the bowlders, showing that they are due to the same cause. Perfect soil on perfect sound rock always shows that the soil has not been formed *in situ*, but has been *shifted* : the *polishing*, *planing*, *scoring*, etc., of the rock show that the *agent* of the shifting has been *ice*.

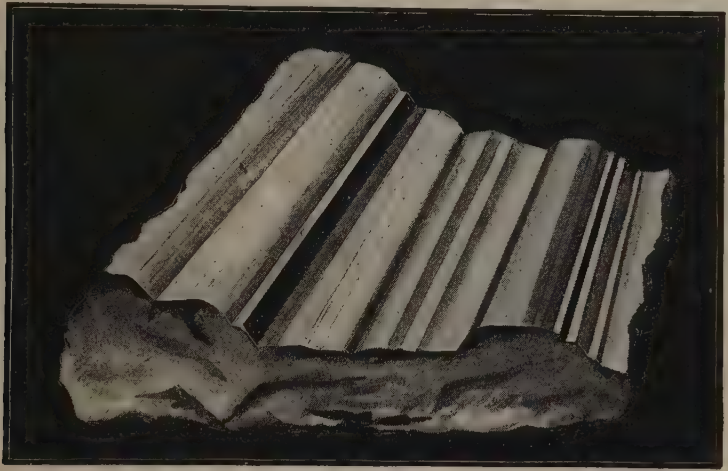

FIG. 947.—Glacial Flutings of Bed-rock, near Burlington, Iowa, × $\frac{1}{18}$ (after Keyes).

Extent.—The general extent of these more conspicuous and characteristic phenomena, viz., the *glaciation*, the *stony clay*, and the *great bowlders*, is down to about 40° north latitude. The line of southern limit cuts the Atlantic coast about 40°, near New York ; it then bends a little southward to 37° 30′ in Southern Illinois, and then turns a little northward again as it passes west, and may be traced northwestward nearly to Montana (Fig. 949), and reappears on the Pacific slope in the southern portion of British Columbia (Dawson). South of this line the characteristic phenomena mentioned above are not found except as produced by local glaciers in high mountains, as in Colorado, where the glaciation and the moraines are very conspicuous (Fig. 948). But in the valley of the Mississippi, and on each side to a considerable distance, a superficial gravel and pebble deposit, containing northern bowlders—called by Prof. Hilgard "La Fayette Formation"—extends to the shores of the Gulf.*

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* There is much discussion about the age and origin of this deposit. It probably belongs to the earliest Quaternary, or else the latest Pliocene. But whether it is a torren-

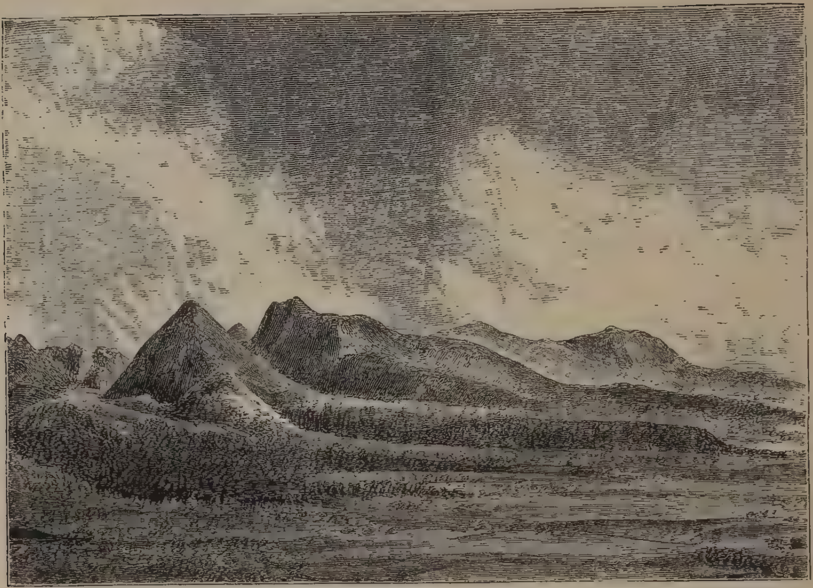

FIG. 948.—Moraines of Grape Creek, Sangre del Cristo Mountains, Colorado (after Stevenson).

Marine Deposits.—Along the Atlantic coasts we find no marine deposits of this time, for the obvious reason that the continent was then more elevated than now; whatever marine deposits were then formed are now covered by the sea.

Theory of the Origin of the Drift.

When the phenomena of the Drift were first observed, they were supposed to indicate the agency of powerful currents, such as could be produced only by the most violent and instantaneous convulsions. A sudden upheaval of the ocean-bed in northern regions was supposed to have precipitated the sea upon the land, as a huge *wave of translation*, which swept from north toward the south, carrying death and ruin in its course. Hence the deposit was often called *Diluvium* (deluge-deposit). *Now*, however, they are universally ascribed to the agency of *ice* acting *slowly* through great periods of time. Hence the name *Glacial epoch.*

As to the *manner* in which the ice acted, however, opinions have been more or less divided, some attributing the phenomena to the agency of land-ice—*glaciers*—others to that of drifting *icebergs.* According to the one, the land during this epoch was greatly raised and covered with glaciers; according to the other, the same area was sunk several

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tial deposit indicating elevation (Hilgard), or a marine deposit and indicating subsidence (McGee), is not yet settled.

thousand feet and swept by drifting icebergs, carried southward by currents, and dropping their load of earth and stones. The one is called the *glacier* theory, the other the *iceberg* theory.

It is probable that *both* these agencies were at work, either at the same time or consecutively; but the decided tendency of science is toward the recognition of glaciers as the principal agent during this *earlier* epoch of the Quaternary. The more the phenomena are studied, and the more glaciers are studied, especially in polar regions, the larger is the share attributed to this agency. We will not discuss this question, but simply give the present condition of science on the subject.

Statement of the most Probable View.—The most probable view for America, and also for other countries, is, that the Drift, or at least the most characteristic phenomena of the Drift, viz., the *glaciation*, the *unsorted bowlder-clay*, and in many cases also the great *traveled bowlders*, are due to the action of *glaciers*. They are therefore a *land-deposit*, and not a sub-aqueous deposit. For general proof of this, let any one study the phenomena of *living* glaciers, in the Alps and elsewhere; then let him study the appearances left by the *recently dead* glaciers of the Sierra; and then let him study the phenomena of the Drift, especially the stony clay and the underlying glaciated surfaces. It will be impossible for him to come to any other conclusion than that the same agent has been at work in all these. In some cases still more conclusive evidence is found in the existence of distinct *terminal moraines*.

Objections answered.—Many objections have been brought against this view, which may be compendiously stated as follows: 1. In glacial regions, like Switzerland, the Himalayas, etc., the glaciers run in *all directions;* but the Drift was carried over wide areas, in a *general direction*. Such a general direction is easily accounted for by the action of icebergs carried by marine currents. 2. The agent of the Drift seems to have been often uninfluenced by the direction of valleys and ridges even of considerable size; thus, for instance, bowlders are carried across valleys 500 or 1,000 feet deep, and lodged as high up on the mountain-slope on the other side. This is perfectly consistent with the action of icebergs drifting over an uneven sea-bottom, but inconsistent with our usual notions of glacial action. 3. The great distance carried, sometimes one hundred miles or more, is precisely what we might expect of icebergs, but difficult to reconcile with our usual notions of glaciers. 4. Alpine glaciers will not move on a slope of less than 2° or 3°, but such a slope, carried several hundred miles, would produce an *incredible elevation of land*. A slope of $2\frac{1}{2}°$ for 200 miles would produce an elevation of nearly nine miles!

These were unanswerable objections so long as our ideas of glaciers were confined to those of temperate climates; but they all find their complete answer in the phenomena of the *polar ice-sheet.* Greenland is 1,200 miles long and 400 or 500 miles wide. This whole area of over a half-million of square miles is covered 3,000 to 6,000 feet deep with ice.* This ice-mantle moves *en masse* seaward, molding itself on the surface inequalities of the country, and chiseling that surface beneath itself, producing *universal* glaciation, and only separating into distinct glaciers at its margin. In *antarctic* regions, the general ice-sheet is even still more extensive and thick. Its extent has been estimated as 4,000,000 to 8,000,000 square miles, and its thickness 10,000 feet. Now, it is to such an ice-mantle that the Drift is to be ascribed, for it moves *irrespective of smaller valleys*, in *one general direction* over great areas, to *great distances*, and over a slope of only 1° or even ½°.

Probable Condition of Things in the Eastern part of the Continent during the Glacial Epoch.—The continental elevation, which commenced in the Pliocene, culminated during this time. In the northern part of the continent it probably reached 2,000 to 3,000 feet above its present level. The shore-line was at least as far out as the submerged continental margin, and all the coast islands of this part were added to the continent. The evidence of this is found in submarine channels off the mouths of all the great rivers, such as the St. Lawrence, the Hudson, the Delaware, etc., trenching the submerged continental plateau and deeply notching its border; for these were evidently formed by erosion during the Tertiary. The axis of elevation was the Canadian Archæan highlands, and thence it became less both northward and southward, but undoubtedly extended to the shores of the Gulf. Coincidently with this elevation, and presumably as its effect, the whole northern part of the continent was covered with a general ice-sheet, 10,000 feet thick over Canada, 6,000 feet over New England, and thinning southward. From this Archæan area as a radiant the ice moved with slow, glacial motion southeastward, southward, and southwestward over New England, New York, Ohio, Illinois, Iowa, and Dakota, regardless of all but the greatest inequalities—filling the valleys, sweeping over the mountain-tops, and glaciating the whole surface in its course. Northward the sheet perhaps extended to the poles, although it was thickest on the Archæan axis; for there are evidences of a northward movement from this axis in some places. Its eastward limit was beyond the present coast-line; its southern limit about 38° to 40° north latitude (Fig. 949). Even farther south, high mountain-ranges, like the Colorado mountains, were ice-covered, and great glaciers streamed down their flanks and left their moraines (Fig. 948). Along the New England coast possibly the ice-sheet in many places ran into the sea and produced icebergs, but wherever the limit was on land, as in the interior of the continent and in some places even on the eastern coast, it probably formed a terminal moraine, but this was feeble, and has been mostly washed away by subsequent erosion.

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* Nansen, Nature, vol. xl, p. 210, 1889.

Terminal Moraines of the Ice-Sheet.—We have already seen that the limit of the ice-sheet—where this was on land—was probably marked by a moraine. Fragments of such a moraine have been found along this limit, especially in its eastern part. Westward it has been mostly washed away by the floods issuing from the melting and retreating ice-sheet. The extreme limit, therefore, in most places is best shown by the presence of glaciation. In one way or another it may be traced throughout its whole extent. Its most northeastern end is found at Cape Cod; thence it goes southwest throughout Nantucket, Martha's Vineyard, and Long Island; thence through Northern New Jersey, Northeastern Pennsylvania, touching the southern border of New York; thence southwest through Ohio to the Ohio River, whose northern border it follows (crossing it, however, once just below Cincinnati) to the Mississippi; thence crossing the Mississippi it follows the Missouri on its south side, and so northwestward through Montana and into British America. This may be called the *ice-sheet boundary.* It is but little affected by topography, passing almost straight over hill and dale. Its moraine is not very distinct now, and probably never was so distinct as that at the later limit.

After reaching this extreme limit, the ice-sheet retreated to, or probably beyond, the Great Lakes, and then *advanced again*, but not so far as before. This second and more recent advance is marked by a *very distinct* and *nearly continuous moraine* of irregular, deeply-lobed outline. In its eastern part this *second ice-sheet moraine* is coincident with, or undistinguishable from, the first already described. But in Ohio the two moraines part company; the second moraine, instead of passing southward to the Ohio River, sweeps in a series of looping curves about the Great Lakes and through Iowa, and thence northwestward on the north side of the Missouri, through Dakota, into British America. The discovery of this moraine, which we owe chiefly to Chamberlin and Upham, must be regarded as a complete demonstration of the existence of the ice-sheet. In the map (Fig. 949) the strong line shows the extreme limit of the *first advance*, the dotted lines the moraine formed by the second advance of the ice-sheet. In its last retreat many subordinate moraines were left one behind another. We have represented mainly the most advanced or else the strongest.

One can not but be struck with the great differences between the first and second advance of the ice-sheet, both as to the character of the border and the distinctness of the moraine. The limit of the first advance is comparatively *even* and its moraine *indistinct.* The limit of the second advance is *deeply lobed* and its moraine very *distinct.* It is probable that both these peculiarities are due to the more active motion of the ice near the border in the second advance. In the first advance the extreme limit was determined not so much by *glacial motion* as by southern limit of perpetual snow. The motion near the border was *sluggish* and the drift border therefore *attenuated.* In the second advance the border was reached wholly by onward *glacial motion,* which, of course, accumulated a distinct moraine. The lobes were in the line of swiftest motion.

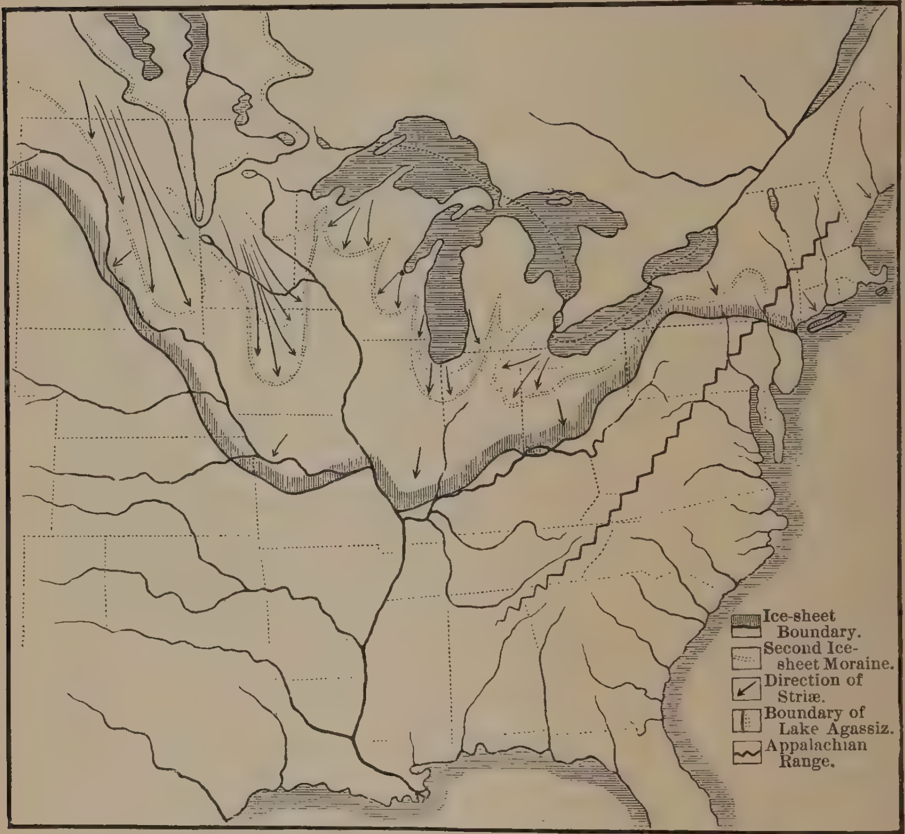

FIG. 949.—Map showing the Extreme Boundary of the Ice-sheet, the Second Ice-sheet Moraine, and the Outlines of Lake Agassiz.

Thus we have clear evidence of a *second glacial* and an *interglacial* epoch. That this interglacial epoch was of considerable length is shown by the existence of a *forest-bed* between the two glacial tills (Newberry), and also by deep erosion-valleys, formed in the drift of the first advance and filled with drift of the second advance. Again, since melting and retreat of the ice-sheet must produce flooding, it is probable that there were two flooded periods. These have doubtless been often confounded with one another.

These two periods of advance and retreat are almost certain. In addition there seems to have been many slighter advances and retreats.

II. Champlain Epoch.

During the Glacial epoch, as just seen, the whole northern portion of the continent was elevated 1,000 to 2,000 feet above the present condition; the northern ice-sheet had advanced southward to 40° latitude, with still farther southward projections favored by local conditions; and an arctic rigor of climate prevailed over the United States even to the shores of the Gulf. At the end of this epoch an opposite or downward movement of land-surface over the same region, probably increased by the weight of accumulating ice, commenced and continued until a depression of 500 to 1,000 feet below the present level was attained. This downward movement marks the beginning of the *Champlain epoch.* As a necessary consequence, large portions of the now land were submerged; it was therefore a time of *inland seas.* Another result, or at least a concomitant, was a moderation of the climate, a melting of the glaciers, and a final retreat of the ice-sheet northward. It was therefore a time of *flooded lakes and rivers.* Lastly, over these inland seas and great lakes loosened masses of ice floated as icebergs. It was therefore pre-eminently a time of *iceberg* action.

Evidences of Subsidence.—The evidences of the condition of things described above are found in old *sea-margins*, old *lake-margins*, old *river-terraces*, and old *flood-plain deposits.*

1. **Sea-Margins.**—Old sea-margins, containing shells and other remains of living species, are found all along the Northern Atlantic coast, becoming higher as we pass northward. In Southern New England the highest beaches are 40 to 50 feet; about Boston they are 75 to 100 feet; in Maine they are 200 feet and upward; on the Gulf of St. Lawrence they are 470 feet; in Labrador 1,500 feet (Upham). In arctic regions they are in some places 1,000 feet (Dana). The beaches may be traced up both sides of the St. Lawrence River, and thence around *Lake Champlain*, where the highest is 500 (Baldwin) feet above tide-level. Upon the beaches about Lake Champlain have been found abundance of *marine* shells, and also the skeleton of a *stranded whale.* Evidently there was here a great inland sea connected with the ocean through the Gulf of St. Lawrence; and over this sea icebergs must have floated. This condition of things has given name to the epoch.

In the subsequent re-elevation of the continent, this *salt lake* (as it must have been at first) was gradually rinsed out and freshened by river-water discharged through the lake and into the St. Lawrence River, as already explained on a previous page (p. 82). All the crust-oscillations characteristic of this period are detectable, also along the South Atlantic and Gulf coast. During the early Quaternary (Glacial epoch) the continental elevation is shown by the powerful erosion of the La Fayette formation, referred by McGee to the latest Pliocene and by Hilgard to the early Quaternary. During the period of *subsidence*, the coastal plains were again covered by the sea, and the shore was again at the fall-line. The deposits of this time form the *Columbian formation* of McGee. Finally, from this subsided condition the land rose to its present level, forming a succession of terraces between the highest, already described, and the present condition.

2. **Flooded Lakes.**—All the lakes in the region affected by the Drift show unmistakable evidences of a far more extended and higher condition of the waters than now exists. About all these lakes is found a succession of terraces or old lake-margins. The highest of these marks the highest water-level, and is the *oldest;* the lower ones mark successive steps in the *draining* away or *drying* away of the waters.

For example, about Lake Ontario successive margins are found up to 500 feet above the present lake-level; about Lake Erie up to 250 feet; about Lake Superior, up to 602 feet (Lawson); and similar margins are found about Lakes Michigan and Huron. It seems not improbable that the retreating ice-front acted as a barrier, against which accumulating water formed one or more enormous lakes, over which floated icebergs loosened from the Canadian ice-foot. These lakes drained southward into the Ohio and Mississippi until the barrier was removed by the final retreat of the ice-sheet; and then northeastward, as now, through the St. Lawrence.

Lake Agassiz.—A great glacial lake in the region of Lake Winnipeg, probably formed in the same way, was first discovered and figured by General (then Lieutenant) Warren, but recently traced out with accuracy by Upham. The retreating ice-front acted as a dam, against which the waters of the melting ice-sheet, together with the natural drainage of this region, accumulated to form a lake of enormous dimensions—greater than all the present Great Lakes put together. This great glacial lake drained southward through the Minnesota into the Mississippi. With the final retreat of the ice-sheet, the drainage was reversed, and its dwindled remains—Lake Winnipeg—drained, as now northward, into Hudson Bay. The outlines of this ancient lake have been accurately mapped by means of its still existing terraces and it has been named Lake Agassiz, in honor of the great champion of land-ice as the cause of the Drift. In map, Fig. 949, we have given the outlines, taken from Upham, of the southern portion of this ancient lake. It has been traced by Tyrrell 150 to 170 miles northward in Canada,[*] and more recently its whole outline has been mapped by Upham.[†]

Both the elevation of the previous epoch and the subsidence of this seem to have been *greater along the axis of the continent, the valley of the Mississippi, than on the coasts.* Hilgard finds evidence in the La Fayette deposit, and in the thickness of the subsequent Champlain deposit, of an elevation of 450 feet above the present level, and a depression of 450 feet (for this is the maximum elevation of the Champlain deposit above the same level), or an oscillation of 900 feet in Louisiana. The submarine channel of the Mississippi, recently found beyond the limits of the delta deposit, show an even much higher elevation in the Gulf region (Spencer). Farther north it is probably still greater.

From this flooded condition the lakes drained away by re-elevation of the land, leaving successive terraces down to their present levels. The re-elevation was greater northward where the subsidence was greatest. This is well shown by the terraces of Lake Agassiz, which are not now level, *but rise toward the north.*

3. **River Terraces and Old Flood-Plain Deposits.**—Nearly all the rivers in the eastern portion of the continent, over the Drift region, are bordered with high *terraces*, which have been cut wholly out of an old flood-plain deposit belonging to the Champlain epoch. In fact, these rivers show first an elevation, then a depression, and finally a partial re-elevation; in other words, all the oscillations of the Quaternary period are recorded by them.

An examination of the rivers north of the fortieth parallel shows: 1. An *old river-bed* far deeper and broader than the present; 2. This deep and broad river-bed is filled up, often several hundred feet deep, by *old river-deposit;* 3. Into this old river-deposit the shrunken stream is again cutting, but is still far above the bottom of the old river-bed. This cutting into the old river-deposit produces bluffs and terraces on each side. It is evident that the great river-bed was gouged out during late Tertiary and early Glacial epochs; the filling up took place during the Champlain, and the cutting and terracing during the re-elevation to the present condition. Some of these old river-channels, as, for example, that of the St. Lawrence, the Hudson, and the Delaware, may be traced far out to sea, to the sunken borders of the glacial continent.

Fig. 950 is an ideal section across a river-bed in the Drift region, in which *b b* is the old river-bed, scooped out during the epoch of elevation; the dotted line represents the highest level to which the old

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[*] Bulletin of the American Geological Society, vol. i, p. 404.

[†] Geological Survey of Canada, vol. iv, E, p. 10, 1890.

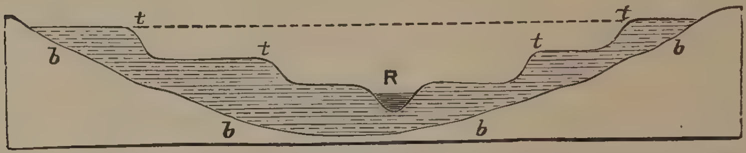

FIG. 950.—Ideal Section across a River-bed in Drift Region: *b b b*, old river-bed; *R*, the present river; *t t*, upper or older terraces; *t′ t′*, lower terraces.

river-deposit accumulated, and the shaded portion that part of such deposit which still remains. The upper terraces, *t t*, are of course the oldest, the lower ones being made as the shrunken stream cut deeper and deeper.

These phenomena are shown in all the river-beds of the Drift region, but especially by those of the Mississippi basin. Sometimes there is only one terrace or bluff; sometimes there are several, on each side. The Connecticut River is a good example of the latter, the Mississippi River of the former.

The Connecticut River is bordered on each side by a succession of terraces rising one above and beyond the other, composed wholly of old river-deposit. Beyond this, of course, is the country rock of Jura-Trias sandstone, covered more or less with drift.

The *Mississippi River* is bordered on each side by its present flood-plain deposit, or river-swamps. This, as already said (p. 25), extends from the mouth of the Ohio River to the head of the delta, a distance of 500 miles, and has an average width of thirty miles. This, its present flood-plain deposit, is limited on the eastern side by bluffs in some places 200 to 400 feet high, composed of Tertiary strata, capped with an old river-silt, or Loess, fifty to seventy feet thick, and this, again, covered by a yellow loam, which extends beyond the limits of the Loess. A layer of La Fayette sand separates the Loess from the Tertiary. Patches of the Loess or *bluff-deposit* are found also on the western side, showing that the *old* flood-plain extended beyond the present flood-plain on both sides; but on the west side it has been mostly removed by subsequent erosion. Also similar deposits, often of great extent, form banks on each side of all the great tributaries of the Mississippi. *Beneath the present river swamp-deposit is found*, by borings, a deposit belonging, like the Loess, to the Champlain epoch, but to an earlier period, probably an estuary deposit, and called by Hilgard "*Port Hudson*," varying in thickness from thirty feet at Memphis to several hundred feet in the delta. Beneath this is first the La Fayette sand and then the Tertiary.

All these facts are represented in the ideal section of the river and the strata in its vicinity, given below, constructed from the investigations of Prof. Hilgard. It is evident that a great trough was hollowed out in the Tertiary strata during the late Tertiary and early Glacial epoch, filled with deposit to the level *l l* during the Champlain, and again partly cut out during the subsequent re-elevation.

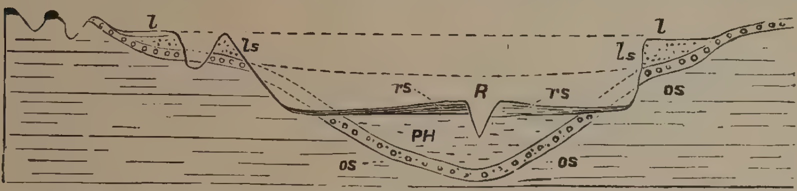

Fig. 951.—Ideal Section across Mississippi below Vicksburg: *OS*, Orange sand or La Fayette; *PH*, Port Hudson, estuary deposit, Champlain; *ls*, Loess or old flood-plain deposit, Champlain; *l*, loam covering the Loess, but more extensive; *rs*, river-swamp deposit, modern.

The cause of the flooded condition of the rivers and lakes was partly the depression of the land, by which the sea entered into the old glacial beds, forming estuaries; partly the smaller angle of slope of the rivers, by reason of which the waters in their lower parts ran off less rapidly, and therefore were more swollen, and therefore also deposited more sediment; and partly the greater abundance of the water-supply, from the melting of the glaciers. The mud-supply also was then very great, as shown by the immense deposit, and also by the cross-bedding (p. 181) so common in these deposits.

During the re-elevation the rivers cut deeper and deeper into their old flood-plain deposits, producing sometimes many smaller terraces, as in the Connecticut, sometimes one large bluff, as in the Mississippi. As the re-elevation was not the same in all parts of the continent, but greater northward and eastward, many rivers, especially in the southern part of the Drift region, *reversed their courses* after the withdrawal of the ice-sheet.

Origin of the Loess.—Over large areas bordering the Mississippi and its tributaries, and forming the conspicuous bluffs of these rivers, there is found a peculiar deposit of very fine, even-grained, and usually unstratified material, remarkable for forming by river-erosion perpendicular walls—although soft enough to be easily spaded. It is usually destitute of organic remains, but when these are found they consist of fresh-water shells, and especially of *land-shells.* When fresh-water shells are found, the material is usually obscurely stratified. Similar bluff-materials are found bordering nearly all the European rivers, such as the Rhine and Danube, and is there called *Loess*, and referred to the Champlain epoch.

A somewhat similar material, however, is found also spread almost evenly over wide areas in many countries, especially in arid regions, and having no obvious connection with any rivers. Such is especially the case in Northern China, where Richthofen finds it covering thousands of square miles, and in places one thousand or more feet thick. Russell also finds a somewhat similar unstratified deposit covering large areas of the Basin region, and sometimes locally called "*adobe*."

There has been much discussion about the origin of these deposits. The Loess of the Mississippi and its tributaries, as also the European rivers, was probably deposited in the flooded lakes and in the slackened waters of the flooded rivers of the later Glacial and Champlain epochs. It is poor in fossils, because the waters were *ice-cold*. It is unstratified, because the waters were *overloaded* with the very finely triturated material left by the retreating ice-sheet.

The Loess of Northern China, Richthofen thinks, is *an Æolian deposit*—i. e., a deposit of wind-borne dust from the arid regions to the northwest.* The unstratified superficial soil of the Basin region, Russell thinks, is due partly to wind-borne dust, but mainly to *rain-wash* —i. e., to the semi-liquid, creamy mud washed down the bare slopes by heavy rains; for in these arid regions, although rain is rare, it falls in torrents.† The unstratified soil, often called Loess, covering the hilly country at the base of the Alps, is attributed by Sacco to rain-wash of the bare soil recently left by the retreating ice.‡

It is probable, therefore, that several kinds of deposit, having a superficial resemblance, have been confounded under the common term of Loess, and that more observation is necessary to clear up the subject.

Origin and History of the Great Lakes.—The origin of these lake-basins is still doubtful. They probably did not exist in the Tertiary period, but in their place was a great depression draining northeastward. During the *Glacial epoch* this depressed area was swept out and perhaps deepened by the advancing ice-sheet. The irregular *gouging* of the ice-sheet, the irregular *choking* of the drainage area by *débris* left by its retreat, and especially the irregular *warping* of the earth-crust in re-elevation, rising more northeastward, probably gave origin to the lakes. In the *early Champlain*, as already said, they were all united into one immense sheet draining southward through tributaries of the Ohio and Mississippi, the natural drainage northeastward being prevented by the ice-foot. Then, by the retreat of the ice northward and the accompanying continental elevation, this one lake was broken up into several, which found an outlet eastward through the Mohawk

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* American Journal of Science, vol. xiv, p. 487, 1877.

† Russell, Geological Magazine, vol. vi, p. 289, 1889.

‡ Archives des Sciences, 1889, vol. xxi, p. 355.

Valley and Hudson River into the Atlantic. Finally, by further retreat of the ice-foot, they drained northeastward, as now, through the St. Lawrence River. At one time during these changes the three upper lakes seem to have found a separate outlet through the Ottawa into the St. Lawrence.

History of the Mississippi River.—It may be interesting to stop a moment, and trace, briefly, the history of this great river. During the *Cretaceous period*, the Ohio probably ran into the embayment of the Gulf, represented in Fig. 760 (p. 486); but the Mississippi probably did not yet exist. The drainage of all that part of the continent was, doubtless, into the great interior Cretaceous sea. At the beginning of the *Tertiary period*, the Mississippi probably commenced to run into the Tertiary embayment, shown in Fig. 852 (p. 524). The Red and Arkansas, if they then existed, were not tributaries, but separate rivers, emptying into the same embayment. The Ohio was almost, if not quite, a separate river also. During the early *Glacial epoch*, the whole embayment of the Gulf was abolished by elevation. This is clearly demonstrated by the torrential pebble-deposit (La Fayette formation), and by the stump-layer (old forest-ground), found by Hilgard beneath ing Port Hudson (Champlain) deposit, on the shores of the Gulf. Dur-the the *same epoch*, by reason of this elevation, the great trough, represented in Fig. 951, was scooped out of the Tertiary strata, 200 to 500 feet deep, by the erosive power of water, favored by the greater slope of the country southward at that time, and also by the greater water-supply. During the *Champlain epoch*, by subsidence this great trough became an arm of the Gulf, or an estuary, fifty to one hundred miles wide, and reaching up to the mouth of the Ohio, with extensions up the tributaries; and this estuary became filled, 200 to 500 feet deep, with sediments. This deposit was at first estuarian (Port Hudson), and afterward river-silt (Loess). At the same time the Mississippi was connected with the Great Lakes, then greatly enlarged, and with Lake Winnipeg, then also greatly enlarged, as Lake Agassiz. During the re-elevation, this silt was laid bare, and the river commenced and continued to cut, until the bluffs became 200 to 400 feet high. Finally, during the *Recent epoch*, the river has again commenced *building up* by sedimentation, showing thus a slight depression again, or at least a *cessation*, of the re-elevation. This up-building by sedimentation has continued up to the present moment, and the deposit (river-swamp and delta deposit) has reached, according to Hilgard, a thickness of fifty to a hundred feet.

Quaternary Period on the Western Side of the Continent.

All the most characteristic phenomena of this period, such as old *sea-margins*, general *glaciation*, *flooded lakes*, and *old river-beds*, are abundant and conspicuous on the western side of the continent. As it is impossible to synchronize perfectly these phenomena with those already described on the eastern side, it will be best to take them in the order named above and trace each kind through the whole period.

1. **Sea.**—The phenomena along the sea-coast show both elevation and depression. A more elevated condition than the present is shown by the bold, rocky coast and high island standing a little way off the coast. The islands off the coast of the southern part of California, and separated from the mainland by the Santa Barbara Channel, are evidently continental islands. They were undoubtedly a part of the continent during the late Tertiary and early Quaternary times, and were separated subsequently by subsidence. This is clearly shown by their flora,* and especially by the remains of the Mammoth on one of them —Santa Rosa.† Another very striking proof of continental elevation is found on this, as on the Eastern coast, in the existence of deep submarine channels cutting through the submerged continental plateau, and evidently produced by subaërial erosion during late Tertiary times. I am indebted to Prof. Davidson for facts concerning these. There are about twenty of these off the California coast, nine or ten of which are very marked. Commencing at Cape Mendocino, and going southward, four very deep ones are found in twenty-five miles—one, very marked, in the Bay of Monterey, one in Carmel Bay, one off the eastern entrance of Santa Barbara Channel, two in the Bay of Santa Monica, and one off the harbor of San Diego. These channels show a previous elevation of 2,500 to 3,000 feet. But there is one peculiarity of these as compared with those on the Eastern coast, viz., that they do not, in any evident way, correspond to the mouths of the present rivers, but, on the contrary, often abut against a bold coast, rising to 3,000 feet within three miles of shore. The explanation of this difference is found in the enormous orographic changes which occurred on this coast in early Quaternary times. Of this we will speak again.

Subsequent *subsidence* and partial re-elevation are still more clearly shown by raised sea-margins. Lawson, confirming Davidson, finds 12 to 15 terraces at San Pedro and up to 1,200 feet above sea-level. He has also found on the island of San Clemente 20 successive terraces up to 1,500 feet above sea-level. Similar terraces are found also at Santa Cruz up to 1,200 feet, and near Montery up to 800 feet. It is doubtful, however, whether these are Champlain or earlier. Lawson thinks them Pliocene. During this period of subsidence (Champlain), the Bay of San Francisco covered all the flat lands about the bay, and all the valley continuations of the bay, north and south, such as Sonoma and Napa Valleys on the north and Santa Clara Valley on the south. Also the sea then passed through the Strait of Carquinez and covered the whole San Joaquin and Sacramento plains, forming a great interior sea 300 miles long and fifty miles wide. The margins of this sea are still visible in the upper Sacramento Valley. At the same time the sea entered the Columbia River and spread over the Willamette Valley, forming a great sound, and passed up to, and possibly beyond, the Cascades. About Puget Sound similar evidences of former extension are plain, especially at the southern end; while in British Columbia Dawson finds old sea-margins up to 2,000 or even 3,000 feet above the present sea-level. Since that time, the coast-line has been re-elevated to its present level, leaving successive lower terraces which are conspicuous in some places. Lake Tulare is a remnant of the interior San Joaquin Sea, although it was probably first freshened by an outlet into the San Joaquin River, and again salted by loss of its outlet.

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* American Journal of Science, vol. xxxiv, p. 457, 1887.

† Proceedings of the California Academy of Science, vol. v, p. 152. The remains of two more elephants were found on Santa Rosa, in October, 1890, by Mr. C. D. Voy.

2. **Ice.**—We have already (p. 276) spoken of a great elevation of the Sierra Range, which occurred at the beginning of the Quaternary. This mountain-lifting doubtless contributed to the development of glacial phenomena at this time, but must not be confounded with the general continental elevation which took place at the same time, as shown by the sea-margin phenomena.

During the fullness of glacial times—as shown by Dawson *—a continental ice-sheet covered nearly the whole of British Columbia, Northwest Territory, and Alaska, connecting in high latitudes with the Eastern sheet. The center of radial movement was a high area extending from 55° to 59° north latitude. From this area the ice moved southward, southwestward, westward, and even northwestward. Southward it certainly reached beyond 48°. Westward it flowed over the Coast Ranges, filled the valleys (now submerged) separating the great coast islands from the mainland, flowed over these islands, and ran into the sea beyond.

At the same time it is certain that the Sierra † was completely mantled with snow; and great glaciers, some of them forty to fifty miles long filled all the profound cañons which trench its flanks. At the same time also there is some evidence that even the Coast Ranges, favored by proximity to the sea, had their perpetual snow-cap from which issued glaciers filling the principal valleys.‡

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* Geological Magazine, vol. v, p. 347, 1888.

† For a fuller account of the glaciers of the Sierra, and the condition of things during the Glacial epoch, see American Journal of Science, vol. iii, p. 325, and vol. x, p. 26.

‡ Undoubted marks of ancient glaciers are found about Berkeley, 300 feet above the bay.

It is impossible to describe all the great ancient glaciers whose tracks have been traced. They filled all the larger cañons, and their tributaries all the higher and smaller valleys and meadows. Their tracks are everywhere marked by glaciation and strewed bowlders, and their terminus at different times by a succession of terminal moraines and lakelets. We will mention three or four as examples:

a. During the epoch spoken of, a great glacier, receiving tributaries from Mount Hoffman, Cathedral Peaks, Mount Lyell, and Mount Clark groups filled *Yosemite Valley*, and passed down Merced Cañon. The evidences are clear everywhere, but especially in the upper valleys, where the ice-action lingered longest.

b. At the same time tributaries from Mount Dana, Mono Pass, and Mount Lyell, met at the Tuolumne meadows to form an immense glacier, which, overflowing its bounds a little below Soda Springs, sent a branch down the Tenaya Cañon to join the Yosemite glacier, while the main current flowed on down the Tuolumne Cañon and through Hetchhetchy Valley. Knobs of granite, 500 to 800 feet high, standing in its pathway, were enveloped and swept over, and are now left round, and polished, and scored, in the most perfect manner. This glacier was at least forty miles long and 1,000 feet thick at Soda Springs, for its stranded lateral moraine may be traced so high along the slopes of the bounding mountain, and 2,500 thick farther down, for it filled Hetchhetchy Valley to the brim.

c. The Sierra Range on its western side slopes gradually for fifty or sixty miles; but on the eastern side it is very precipitous, so that the plains 5,000 to 7,000 feet below the crest are reached in four or five miles. In glacial times long and complicated glaciers with many tributaries occupied the western slope, while on the eastern slope innumerable short, simple glaciers flowed in parallel streams down the steep incline and out for several miles on the level plain, or even into the waters of Lake Mono. One of the largest of these took its rise in the snowfields about Mono Pass, flowed down *Bloody Cañon*, and six to seven miles out on the plain, and evidently into the waters of Lake Mono, which was then far more extensive and higher than now. Parallel moraines, 300 feet high, formed by the dropping of glacial *débris* on each side of the icy tongue, as it ran out on the plain or on the bottom of the shallow lake, are very conspicuous, as are also the successive *terminal* moraines left in the subsequent retreat. Behind these moraines water has accumulated, forming lakelets.

d. Many glaciers, whose tracks are still easily traced, at that time ran down the steep mountain-slope into Lake Tahoe. The most conspicuous of these are three at the southern end, which, issuing from as many cañons, ran out on the level plain three or four miles, and into the swollen waters of the lake to form icebergs. The beautiful lakelets and the lake-like bay which form so conspicuous a feature of the scenery of the southern end of the great lake, were partly scooped out by these steeply descending glaciers, and partly dammed by the *débris* left when they retired; and the long, parallel ridges of earth and bowlders bordering the lakelets and stretching down to the shores of the great lake, are *lateral moraines* dropped on each side as the glaciers ran out into the lake* (Fig. 952).

With the decline of glacial conditions all these glaciers of the Sierra retreated, leaving very distinct terminal moraines, where they rested awhile, behind which, drainage-waters accumulating, have formed beautiful little lakes. Thus they have gone backward and upward, until they have now mostly retired within the snow-fields which gave them birth. The feeble remains of some may still be found hidden away among the coolest and shadiest hollows of the highest summits.

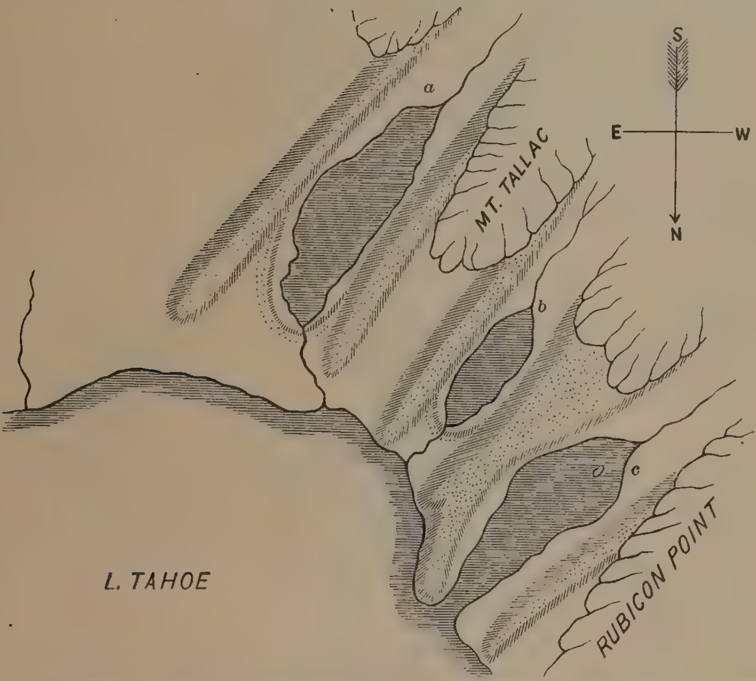

FIG. 952.—Diagram of Moraines at the Southern End of Lake Tahoe: *a*, Fallen-Leaf Lake; *b*, Cascade Lake; *c*, Emerald Bay.

Lakes.—A period of flooded lakes, marked by successive terraces about the present lakes, is well shown, especially in the Basin region. The period of the flooded lakes in this region seems to have corresponded with the Glacial epoch, for the great glaciers ran into some of them.

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* American Journal of Science, vol. x, p. 126, 1875.

About Lake Mono there are five or six very distinct terraces, the highest being about 700 feet above the present water-level. Evidently at that time its waves washed against the steep slope of the Sierra, and many of the glaciers in this region ran into it. About *Salt Lake*, several terraces are very conspicuous, the highest being about 1,000 feet above the present lake-level. Traced out by this highest level, the outline of the lake embraced an enormous area. Similarly about all the saline lakes of the Nevada basin terraces have been traced up to more than 600 feet about the present level. In general terms, we may say that the Basin region at that time was occupied by two great lakes: the one filling the Utah basin, the other the Nevada basin, the eastern shore of the one washed against the Wahsatch, the western shore of the other against the Sierra. The former has been accurately mapped by Gilbert and called Lake Bonneville (Fig. 953 *a*)—the latter, also accurately mapped by King and Russell, and called Lake Lahontan (Fig. 953 *b*), in honor of these early explorers. Lake Bonneville when at its 1,000-foot level, emptied northward into the Snake and Columbia Rivers. It eroded its outlet down to the 600-foot level; there lost its outlet and dried away to its present condition. Lake Lahontan when at its 600-foot level had a complicated, deeply-dissected outline, with the numerous mountain-ridges of the Basin region forming high islands and promontories. So far as known, it had no outlet. As the Quaternary period passed away, these great lakes dried away more and

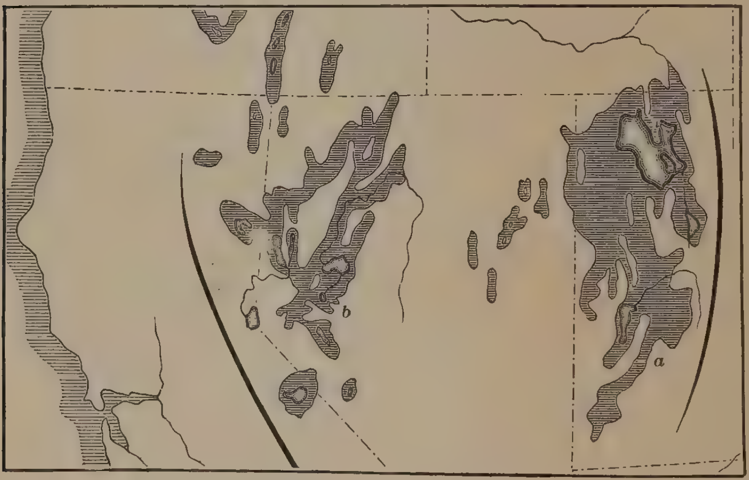

FIG. 953.—Map of the Quaternary Lakes Bonneville (*a*) and Lahontan (*b*) (after Gilbert and Russell).

more. The residues of the one are Great Salt Lake, Utah Lake, and Sevier Lake; of the other, Pyramid, Winnemucca, Humboldt, Carson, Walker, and Soda Lakes. If in the East the Quaternary lakes mostly *drained* away, in the West they mostly *dried* away to their present condition. The map (Fig. 953) gives outlines of these two great lakes and their present residues.

In both of these great lakes, according to Gilbert and Russell, there are abundant evidences of two flooded periods separated by a period of complete desiccation. If the flooded periods correspond with periods of great development of the ice-sheet, as seems probable, we have here also—as in the eastern part of the continent—two Glacial periods separated by an interglacial.

River-Beds.—Old river-beds are found in many countries, and especially in the Drift region of the eastern portion of our continent (p. 581), but those of California are peculiar. In the East and elsewhere, the Tertiary river-beds are in the *same places*, but *below* the present river-beds; in California they are far *above*, and in many cases in *different places*—i. e., the rivers have been *displaced* from their former beds and cut much deeper. In map (Fig. 954) we give a portion of the country about the upper Yuba, and Fig. 955 is an ideal section across the river-beds along the line N S, Fig. 954. It is seen

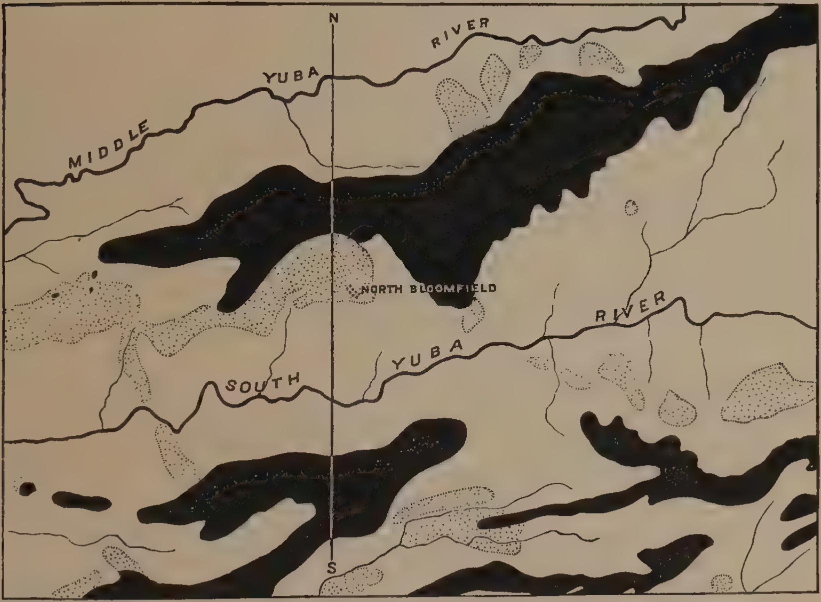

FIG. 954.—Map of a portion of the Region of the Deep Placers of the Yuba River: The black, lava-flows; the dotted spaces, gravel (after Whitney).

that there are remnants of old lava-flows on the divides between the deep river-channels. Beneath these lavas there are river-gravels, and

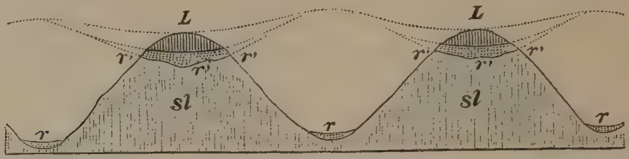

Fig. 955.—Section along the Line, north and south: r' r', **old river-beds;** r r, **present river-beds;** *L*, **lava;** *sl*, **slate.**

beneath these gravels, trough-shaped river-beds with their smoothly and variously eroded bed-rock. The section shows, moreover, that the present rivers have commenced their beds on the old divides (shown by dotted lines), but have *cut much deeper*, leaving the old beds high up on the present divides.

Such are the facts. The history of the process is briefly as follows: At the end of the Tertiary there was an outburst of lava near the crest of the Sierras.* The lava flowed down the river-beds, filled them up, and displaced the rivers. These immediately commenced cutting new beds on *the old divides*, because the lava was thinner or absent there. Now, coincidently with the lava-flow, there was an *elevation of the Sierra crest by tilting of the Sierra crust-block* (p. 276), and therefore increase of the Sierra slope. Such tilting was attended with enormous displacement or faulting on the eastern side, as already explained. On account of the increased slope, the rivers seeking their base-level cut down far below their previous level. This increase of slope is shown, if possible, still more plainly, in some of the rivers of the southern part of the State, beyond the limits of the lava-flow. Here also the tilting and the increased slope took place, but the rivers were

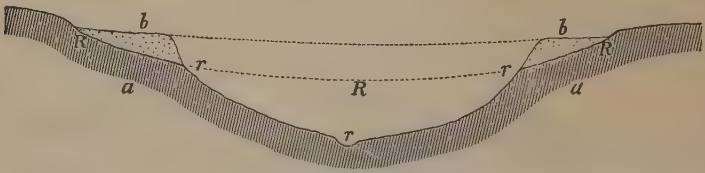

Fig. 956.—Ideal Section across a River-bed in Southern California beyond the Region of the Lava-flow.

not displaced. They, therefore, retained their beds, but deepened their channels, leaving the old river-gravels high up on their sides (Fig. 956).

This elevation of the Sierra took place at the end of the Tertiary or beginning of the Quaternary, and doubtless contributed greatly to the severity of the glaciation in California, but must not be confounded with the northern continental movement, which occurred about the same time, and was far more efficient in determining *general* glaciation. Coincident with the Sierra elevation by block-tilting, as already explained (p. 276), similar orogenic movements took place in the Basin region. Thus it is seen that the river-beds of California show, not continental crust-oscillations like those of the East, but mountain-making by crust-block-tilting.

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* The great lava-flooding of the Tertiary commenced probably at the end of the Miocene, and continued through the Pliocene. These flows, in California, seem to have been the last.

We have seen that the submarine channels of the California coast differ from those of the Eastern coast, in that they are not continuous with the present subaërial river-channels. We have also just seen that the river-beds of the Sierra differ from those on the Eastern coast, in that they have been displaced from their old positions, and have cut much deeper. Now, the reason of this difference is probably the same in the two cases, viz., recent orogenic changes. We have seen that the Sierra took its present form and height at the beginning of the Quaternary. Great orogenic changes occurred at the same time in the Coast Range also, for its Pliocene strata are greatly folded (Lawson). In both cases, too, the orogeny was attended with floods of lava. Much of the lava, and presumably many of the ridges of the Coast Range, were formed at that time. By these changes the *mouths of the rivers were changed from their original places.*

History of the Sierra Range.—This range was born out of the ocean by horizontal crushing and bulging, as already explained (p. 269), at the end of the Jurassic. During the whole Cretaceous and Tertiary it was subjected to erosion, until by the end of that time the rivers had reached their base-levels, and the range was reduced to very moderate height. The crest was then about the region of the Yosemite, for the erosion into the granite is deepest about that region. Then came, at the end of the Tertiary and beginning of the Quaternary, the tilting of the Sierra earth-block, the formation of the great fault-cliff, and the transference of the crest to the extreme eastern side; the outpouring of the lava; the displacement of the rivers; and the cutting of the new river-beds. By this great movement, the already *old* Sierra was rejuvenated, and entered upon a new cycle of changes by erosion, which is still progressing. The sharply accented, even savage character of the scenery of the Sierra is the result of the comparative recency of its latest movement.

The Quaternary Period in Europe.

In Europe the phenomena were more irregular, the oscillations more numerous, and perhaps more local, than in America. This is in accordance with the general difference in the geological history of the two continents. Nevertheless, the general character of the phenomena was similar in the two countries.

1. **Epoch of Elevation—Glacial Epoch.**—During the Early Quaternary the whole of Northern Europe seems to have been elevated 1,000 to 1,500 feet and sheeted with ice. The continental margin was considerably farther west than now. The British Isles were then a part of the continent, there being then no Baltic and North Sea. The area of highest elevation and of thickest ice, and therefore of radial movement, was the Scandinavian Peninsula. From this area the ice moved westward into the Atlantic, as far at least as the line of 100 fathoms (shown by the dotted line, Fig. 957); southwestward over the British Isles, southward over the beds of the Baltic and North Seas and into Northern Germany as far as the frontiers of Bohemia; and southeastward and eastward over Russia, far beyond Moscow, glaciating the whole surface in its course. The southern boundary of the ice-sheet has been traced. It passed through Cornwall, across Dover Strait, through Middle Germany and Southern Russia to the Ural Mountains, following nearly the 50th parallel of latitude. The general outline and extent of the ice-sheet in Europe during the period of its maximum is shown in the map, Fig. 957.

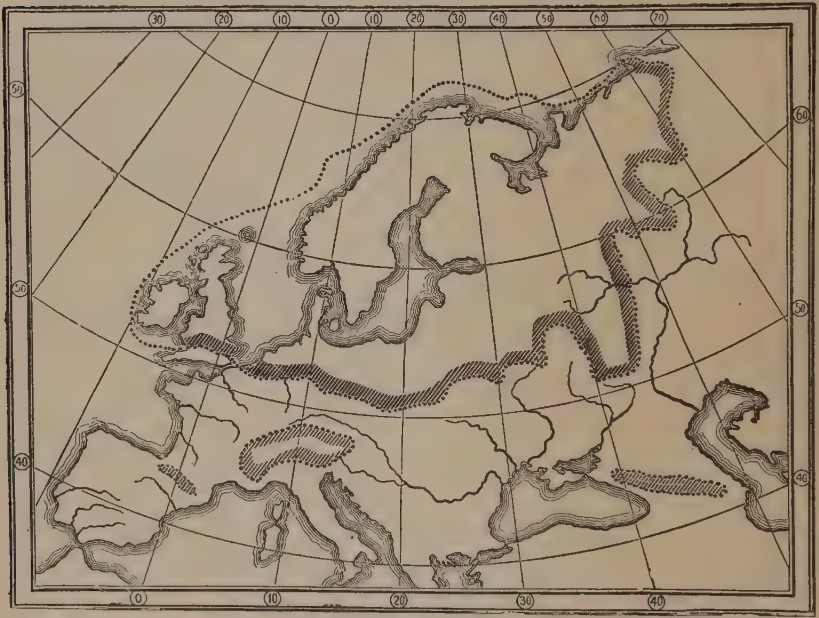

FIG. 957.—Map of Europe, showing the limit of the Ice-sheet and also subordinate Ice-sheets in mountain regions.

At the same time, the whole Alpine region of Middle Europe, although beyond the limits of the ice-sheet, was mantled with snow to a degree much greater than at present, and developed glaciers on a prodigious scale. Some of these have been traced out with great care and skill. Especially has this been done for the *great Rhône glacier* by Guyot, and more recently by Favre. At that time a great glacier came down the valley of the Rhône, emerged on the plains, and filled the whole valley of Switzerland, fifty miles wide, between the Alps and the Jura, forming a great *mer de glace* 50 miles wide, 150 miles long, and 4,000 to 5,000* feet deep. A figure is given below of this great glacier. The dotted lines show the direction of motion as determined by bowlders left in the valley or stranded high up on the slopes of the Jura.

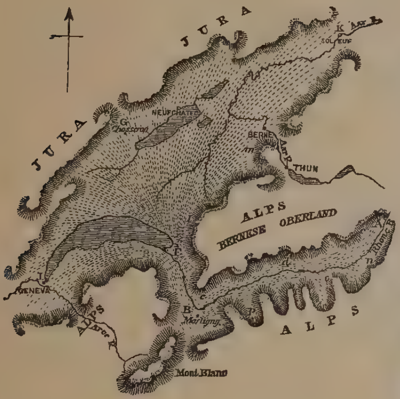

FIG. 958.—Map showing the Outline and Course of Flow of the Great Rhône Glacier (after Lyell).

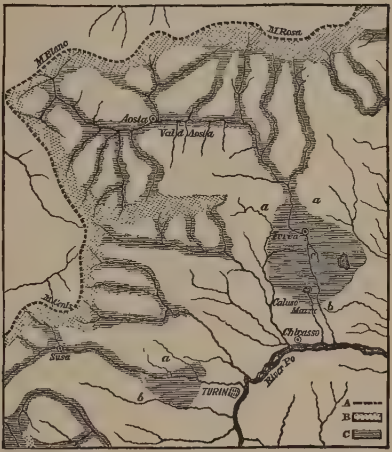

FIG. 959.—Map showing the Lines of *Débris* extending from the Alps into the Plains of the Po (after Lyell).

Lakes Geneva and Neufchâtel were filled and their bottoms scoured by this great glacier.

At the same time, also, on the southern slopes of the Alps, long glaciers stretched out on the plains of Lombardy, as shown by the prodigious piles of *débris* (moraines) still left. Some of these moraines are 1,500 feet high. Fig. 959 is a map of these lines of *débris*.

Evidences of glaciers of this time are also found in the Vosges, in the Pyrenees, and other high mountains of Central Europe.

During this time also Europe was probably connected with Africa by one or more highways, through the Mediterranean Sea.

In Europe, as in America, there are evidences of a temporary retreat and readvance of the ice-sheet—i. e., of two glacial and an interglacial period. Some have made many more; but these two seem well made out.

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* Archives des Sciences, vol. lviii, p. 159, 1877, and vol. iii, p. 228, 1880.

2. **Epoch of Subsidence—Champlain.**—Following the epoch of elevation was an epoch of subsidence, during which the same regions which were before most elevated became now most depressed. It is believed by some that in Scotland the land was 2,000 feet below the *present level.* By this depression a great part of Northern Europe was submerged, and Great Britain was reduced to an archipelago of small islets. Over the area thus submerged icebergs loosened from the Scandinavian ice-fields drifted.

At the same time, partly by subsidence, and therefore slackened water-currents, and partly by moderated climate and melting of glaciers, there was a flooded condition of rivers and lakes in Middle Europe, France, Germany, and Switzerland. At the same time, also, the northern portion of Asia and the lake-region of that continent were submerged. The Caspian Sea, Lake Aral, and other lakes in that region, were probably then united into one great inland sea, connected either with the Black Sea or the then greatly-extended Arctic Ocean, or with both.*

Evidences of this condition of things are found in old sea-margins, lake-margins, river-terraces, and flood-plain deposits.

The subsidence was followed, as in America, by a re-elevation, shown by successive beaches and terraces on sea-shores, about lakes, and along rivers. In some places, the re-elevation seems to have gone beyond the present level, and the British Isles for a brief time were again united to the continent. Then the land went down again to its present condition.

Southern Hemisphere.

Similar phenomena to those described have been observed also in high latitude regions of the Southern Hemisphere, i. e., in the southern parts of South America, Australia, Africa, and New Zealand. Indeed, the facts of distribution of organisms strongly suggest that in glacial times (as also in Permian) Antarctica was greatly elevated, and so extended that it connected with South America, South Africa, and Australia. This condition was attended with glaciation as severe and probably as extensive as that in the Northern Hemisphere, but the subsequent subsidence was greater and more permanent, and therefore much of the glaciated region is now covered by the sea.

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* Nature, vol. xiii, p. 74; Natural History Magazine, vol. xvii, p. 176; Archives des Sciences, vol. liv, p. 427.

Some General Results of Glacial Erosion.

1. **Fiords.**—We have seen that the phenomena of rivers, in the region affected by the Drift, show elevation, then subsidence, and then re-elevation to a less height than the first. The first elevation is shown in their deep, ancient beds; the subsidence, in the filling up of these with deposit; the re-elevation, in the cutting down into the deposit, and forming terraces. Now, all these changes are also shown in the phenomena of *fiords* (Dana).

It will be remembered (p. 38) that the Norway coast is wonderfully bold and deeply dissected, consisting of high, rocky headlands, separated by deep inlets running 50 to 100 miles into the country; and off shore there is a line of high, rocky isles, evidently the remnants of an old shore-line. These deep inlets are called in Norway *Fiords;* and the name is now used for all such deep inlets separating high headlands. The coast of Greenland has a precisely similar structure. It, also, consists of bold, rocky headlands, separated by fiords running far into the country; and off shore a line of rocky isles 2,000 feet high. In Greenland these fiords are now occupied by glacial extensions of the general ice-mantle (Fig. 960). The same coast-structure is found on the western side of the continent in high latitudes. The coast of British America and Alaska is also bold and deeply dissected by fiords; and in Alaska these fiords are now occupied by great glaciers running down to the sea.

The fiords of Norway have been attributed (p. 38) partly to the erosive agency of waves and tides, but it is certain that they are *mainly* due to a partial subsidence of a bold coast deeply trenched with gorges. In a word, fiords are deeply-eroded valleys, which have become *half submerged;* and, as glaciers are the most powerful of erosive agents in these regions, they are usually *half-submerged glacial valleys.* These valleys can in most cases be traced as submarine troughs, far out to sea. In Greenland, for instance, the extension of these troughs, deep below the present sea-level and far out beyond the reach of the present gla-

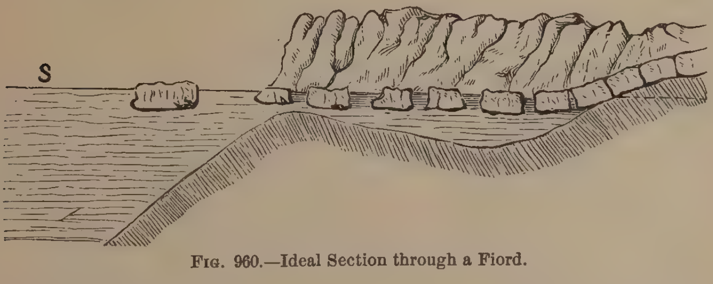

FIG. 960.—Ideal Section through a Fiord.

ciers, shows a former more elevated condition; and terraces and recent deposits up to 500 feet show a subsidence below, and a re-elevation to, the present level.

All shores in northern regions are bold and rocky and deeply dissected, and have rocky islets off shore; in other words, are more or less affected with *fiord-structure.* They have been elevated, eroded, and subsided. It is probable that during the epoch of greatest elevation a *broad continental connection existed* between America and Asia, including the whole area between the Aleutian Isles and Bering Strait.

2. **Glacial Lakes.**—Lakes are found in nearly all countries, and are doubtless due to many different agencies, but the small lakes, so abundant in the region covered by the ice-sheet and by ancient glaciers, are undoubtedly due to glacial agency. It is only necessary to look at a good map of the United States to see at once the great contrast in this regard between the Northern and Southern parts. In the single State of Minnesota there are several thousand lakes. South of the line of the ice-sheet there is not one except in Florida, and there due to entirely different causes.

Glacial lakes are formed in several ways: (*a*) They may be *rock-basins* scooped out by glaciers where the rocks are softer or else where there is a sudden change in the slope of the bed from a higher to a lesser angle; or (*b*) they may be formed by the *damming* of drainage waters behind terminal *moraines* of a retreating glacier; or (*c*) by the disappearance of snow from *old cirques*, the fountains of ancient glaciers. These three kinds are very abundant in all the highest mountains, such as the Sierra or the Colorado; the last among the highest summits, the first high up the valleys, and the second a little way down. Again (*d*) along northern coasts elongated lakes are often formed by the *elevation of fiords.* Many lakes in Norway and Scotland are formed in this way; (*e*) lastly, the thousands of small lakes which over-sprinkle the surface left by the ice-sheet, especially after its second advance, are due to irregular dumping of glacial *débris.*

It is necessary to remember that lakes are ephemeral features of topography. They are inevitably in time either drained away by down cutting of their outlets, or else filled up by sediments brought down from above. This process is especially rapid in mountain-regions. The little glacial lakes are rapidly being filled and converted into marshes and meadows. Everywhere in the Sierra, the region of meadows is the region of the old glaciers. Lakes, then—especially small lakes—are a feature of *new topography.* The topography of all the Southern States is extremely old, while that of the Northern States has been largely determined by the Drift, and is therefore very *new.*

Life of the Quaternary Period.

Plants and Invertebrates.—Remains of the life of the Quaternary, both animal and vegetable, are very numerous, and often very well preserved. Both the plants and the invertebrate animals are almost wholly identical with those now living on the earth. We will therefore dismiss these with one important remark: The plants and the marine shells show *an arctic climate in now temperate regions.* The species found are still living, but *living farther north.* There has been a *migration* of species *northward* since Glacial times. In Tertiary times (p. 526), we noted a migration of forms *southward*, indicating a contrary change of climate at that time.

Mammals.—But the *mammalian* fauna of the Quaternary is almost wholly peculiar. It differs greatly from the Tertiary fauna preceding, and the present fauna succeeding. The species are, moreover, very numerous, and many of them of extraordinary size; for it is the culmination of the mammalian age. It is necessary, therefore, to describe some of them, and the conditions under which they were preserved, and thus to realize in some degree the conditions under which they lived. We will take our first illustrations from Europe, because the remains are more numerous and have been more thoroughly studied there.

Mammalian remains of this time are found in Europe—1. In *caverns*, where in great numbers they have become *entombed;* 2. On *beaches and terraces*, where their floating carcasses have become *stranded;* 3. In *marshes and peat-bogs*, where, venturing in search of food, they have *mired* and perished; 4. In *ice-cliffs and frozen soils*, where they have been *hermetically sealed* and preserved to the present time.

1. **Bone-Caverns.**—The richest sources of Quaternary mammalian remains are undoubtedly *bone-caverns.* These occur in nearly all countries, often along the course of streams, but high above the present stream-level. Their formation and their filling are in some way connected with the floods of the Interglacial and Champlain epochs. They are rich in organic remains to a degree which is almost incredible. One of the most striking peculiarities of these remains is, that they often consist of a *heterogeneous mixture of all kinds*, carnivorous and herbivorous, and *all sizes*, from the Elephant and Cave-bear on the one hand down to Rats and Weasels on the other; sometimes perfect, more often broken, mingled with earth and gravel, forming unstratified *bone-rubbish.* Another peculiarity of these deposits is that they are often covered and, as it were, sealed by a stalagmitic crust formed by subsequent drippings from the roof, and thus preserved against even the suspicion of disturbance to the present time. We give (Fig. 961) a section of the cave of Gailenreuth, with its bone-rubbish and stalagmitic crust.

Among the remains of Herbivores found in bone-caverns, the most remarkable are those of the Elephant, Rhinoceros, Hippopotamus, the great Irish Elk, besides Horses and Oxen. Among Carnivores are the Cave-bear (*Ursus spelæus*), larger than the Grizzly, the Cave-hyena,* the Cave-lion,* the Saber-toothed Tiger (*Machairodus latidens*), with

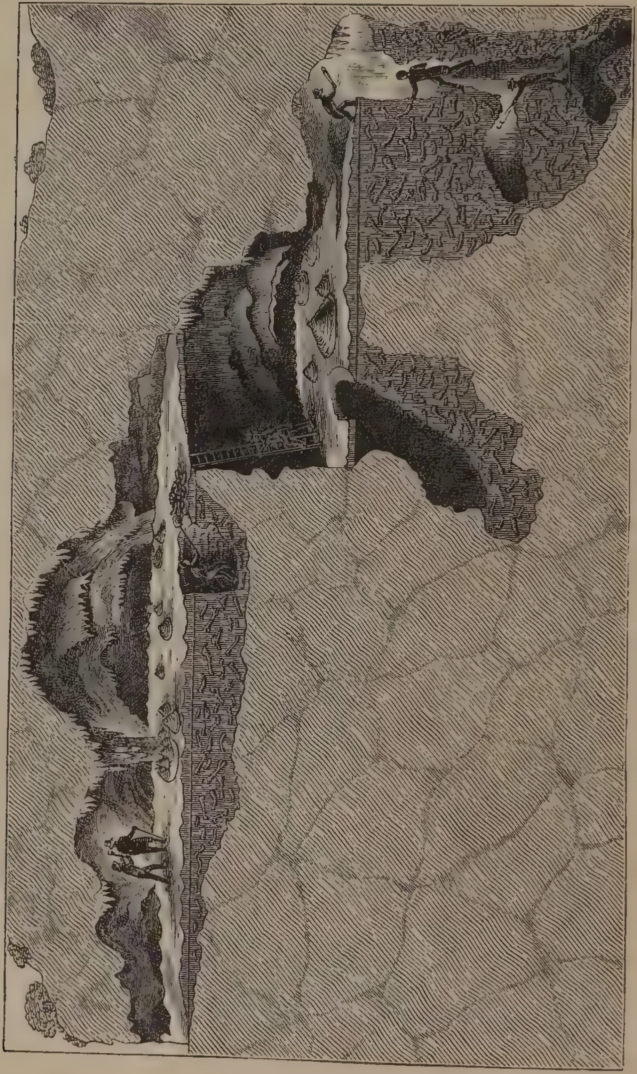

Fig. 961.—Vertical Section through Gailenreuth Cave, Franconia.

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* These are supposed to be the same species as the African lion and hyena of the present day, but much larger.

its saber-like tusks, ten inches long, besides smaller animals of the same order. The remains of the larger Carnivora, especially the Cave-bear and the Cave-hyena, are the most abundant. The *bones of the smaller Herbivores* bear the marks of teeth, as if they had been *gnawed.* The skeletons of the large Pachyderms are usually more perfect. In the Kirkdale Cave, England, the teeth and other parts of 300 individuals of the Cave-hyena were found. In the Gailenreuth Cave, Franconia (Fig. 961), the remains of 800 Cave-bears were obtained. In a Polish cave Römer recently found the remains of at least 1,000 Cave-bears,* and from one in Sicily, twenty tons of hippopotamus-bones have been taken.† In many bone-caves are found also the bones and rude implements of *primeval man.* Of these we will speak more fully hereafter.

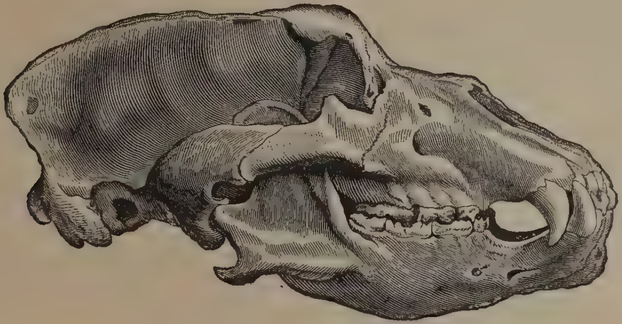

FIG. 962.—Skull of Ursus spelæus, × $\frac{1}{8}$.

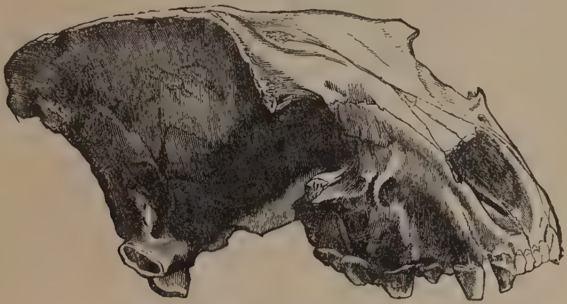

FIG. 963.—Skull of Hyena spelæa, × $\frac{1}{4}$.

Origin of Cave Bone-Rubbish.—When it was supposed that the Drift was caused by a great wave of translation sweeping across the continent and carrying ruin in its course, the phenomena of bone-caves were supposed to give countenance to this view. Animals of all sizes and kinds were supposed to have huddled together in these caves, forgetting their mutual hostility in the sense of a common danger, and perished miserably together there.

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* Science, vol. iii, p. 490, 1884.

† Prestwich, Geology, vol. ii, p. 508.

But at present it is usually believed: 1. That these caves were the dens of the larger Carnivores, especially the Cave-bear and Cave-hyena, which dragged their prey there to devour them, and also later the abodes of men; 2. That also the floating bodies of large Herbivores, such as the Elephant, Rhinoceros, etc., were carried into them by the flooded rivers which then ran at that level; and 3. That during the Champlain epoch, when water ran through these caves in large quantities, bones and earth were drifted in from above, through fissures and subterranean passages, and thus found their lodgment in the caves. This last was probably the principal source of the bone-rubbish in most cases, and it explains also ossiferous fissures, which are common.

Origin of Bone-Caverns.—In limestone regions caverns are very abundant everywhere. They do not seem to be enlarging *now;* but on the contrary to be in most cases filling up either with rubbish or with stalactitic and stalagmitic deposit. In some cases streams still run through them. It seems probable that they are mostly due to the action of subterranean waters in Champlain times. At that time full streams ran through and excavated them, partly by erosion, partly by solution. Gradually, as the re-elevation came on, the great streams into which these cavern tributaries ran cut down their beds to lower levels, the subterranean waters sought lower levels, and the part running through the caverns was reduced to drippings; and stalagmitic crusts covered the Champlain rubbish and preserved them. Thus, then, the date of the *caves* is Champlain; of the bone-rubbish is late Champlain; of the stalagmitic crust is Recent.

2. **Beaches and Terraces.**—On these are found the remains of bodies which have floated and become stranded. The most abundant of these are remains of *Elephas primigenius* or Mammoth. It is believed that the bones of 500 individuals have been found on the coast of Norfolk and Suffolk, and over 2,000 grinders have been dredged up by the fishermen of the little village of Happesburgh (Woodward). On river-terraces associated with bones of Quaternary animals have been found also the rude implements of primeval man already referred to.

3. **Marshes and Bogs.**—As might have been anticipated, the remains found in these are mainly those of the *larger Herbivores*—elephants, oxen, stags, etc. It is in these that were found most of the fine skeletons of the gigantic Irish elk (*Cervus megaceros*). This magnificent elk was ten to eleven feet in height to the top of its palmate antlers, and ten to twelve feet between the antler-tips (Fig. 964).

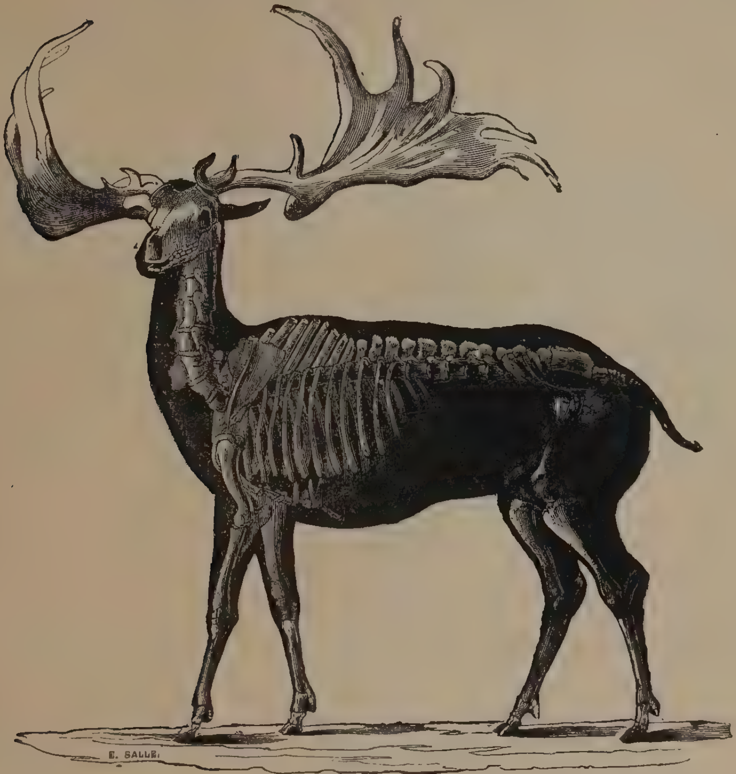

FIG. 964.—Skeleton of the Irish Elk (Cervus megaceros), Post-Pliocene, Britain.

4. **Frozen Soils and Ice-Cliffs.**—As in these have been found the most perfect specimens of the Mammoth (*Elephas primigenius*), this seems to be the proper place to describe the animal.

The genus *Elephas* ranges *in time* from the early part of the Pliocene to the present. There are about fifteen fossil species known. The genus seems to have reached its maximum development in the Quaternary. During that period three species inhabited Europe, viz.: *E. antiquus*, *E. meridionalis*, *E. primigenius* (Lyell), besides two dwarf species, *E. Melitensis*, four and a half feet high, and *E. Falconeri*, three feet high, found in the Quaternary of Malta. Of these, the largest, the most numerous, and the latest, was the *primigenius* or Mammoth. This species roamed in immense herds all over Europe, from the shores of the Mediterranean to Siberia, and extended also over the northern portions of North America. In Siberia the tusks are so abundant and so well preserved that much of the ivory of commerce is got from this source.

The Mammoth (Fig. 965) was over twice the bulk and weight of the largest modern species, and nearly one third taller. It was thickly covered with a brownish *wool*, and in parts with long hair; and was therefore well adapted to endure cold. It may seem strange that we should speak of the hair and wool and the color of an extinct animal; but perfectly-preserved specimens have been found sealed in the ice in Siberia—so perfectly preserved that, when first exposed, wolves and dogs of the present epoch fed on the flesh of this animal belonging to an extinct fauna. The whole skeleton, with portions of the skin, hair, wool, hoofs, and eyes of this animal, is now to be found in the museum at St. Petersburg. The existence of elephants so far north does not indicate a warm climate, although the Champlain epoch was doubtless far less rigorous than the Glacial. These elephants were covered with thick wool, as was also the European rhinoceros of that time.

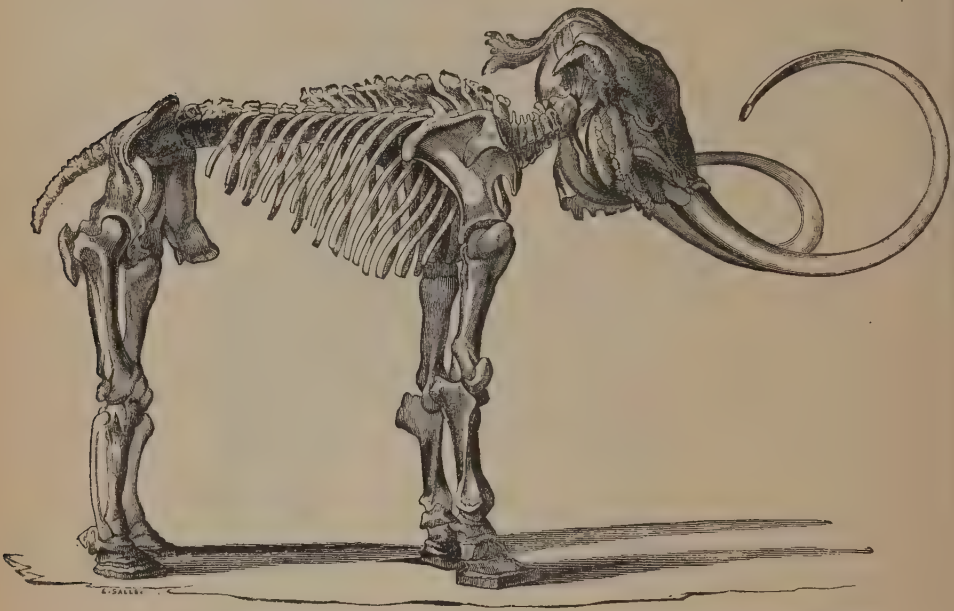

Fig. 965.—Skeleton of the Mammoth (Elephas primigenius). Portions of the integument still adhere to the head, and the thick skin of the soles is still attached to the feet.

Quaternary Mammalian Fauna of England.—In England alone there were, in Quaternary times, of *Carnivora*, the great Cave-bear, the Cave-hyena, a tiger larger than the Bengal, the saber-toothed tiger, as large, with its flat, curved tusks, eight inches beyond the gums, besides wolves and lesser Carnivores. Of *Herbivores*, there were the Mammoth in herds, two species of rhinoceros, one hippopotamus, the great Irish elk, three species of oxen, two of them of gigantic size, besides horses, deer, and other smaller species. Surely this was the culmination of the Mammalian age in England.

Mammalian Fauna in North America.

The animals of North America, in Quaternary times, were equally abundant; but the country has been less perfectly explored, and the collections, therefore, less complete. Bone-caverns, the richest sources of European collections, are also far more rare.

Among *Herbivores*, the most remarkable were the great Mastodon (*M. Americanus*); two species of elephants, the *E. Americanus* and the *E. primigenius;* at least two gigantic bisons, one of which was probably ten feet between the horn-tips;* gigantic horses; gigantic rodents allied to the beaver, one as big as a bear; a gigantic stag (*Cervus Americanus*), fully as large as the Irish elk; tapirs, peccaries, and a large number of *Edentates*, an order now mostly confined to South America, to which belong the sloths and armadillos. Many of these were also of gigantic size. *Carnivores* were not so abundant as in Europe. The most remarkable were a lion (*Felis atrox*), as large as the European, and two species of bear (*Ursus pristinus* and *amplidens*).

We have already seen (page 558) that the Equidæ originated on this continent and migrated to Eurasia. They continued in great numbers throughout the Tertiary, and apparently culminated in the early Quaternary (Equus beds). They soon after became extinct in America and have been reintroduced only in historic times by man.

Bone-Caves.—Caves are found in limestone regions in America as elsewhere, but they do not seem to have been to the same extent the dens of Carnivores. In a vertical opening in limestone strata in Pennsylvania, a kind of cave, mammalian remains have been found belonging to thirty-four species, among which were six Edentates, eight Ungulates, and twelve Rodents. A number have also been found in the caves of Virginia, and a few in those of Illinois (Cope).

Marshes and Bogs.—Most of the remains of large Herbivores have been found in marshes and bogs. In the *Big Bone Lick*, Kentucky, the remains of one hundred mastodons and twenty elephants are said to have been dug up. Many very perfect skeletons of the great mastodon have been obtained from marshes in New York, New Jersey, Indiana, and Missouri. One magnificent specimen was found in a marsh near Newburg, New York, with its legs bent under the body and the head thrown up, evidently in the very position in which it mired. The teeth were still filled with the half-chewed remnants of its food, which consisted of twigs of spruce, fir, and other trees; and within the ribs, in the place where the stomach had been, a large quantity of similar material was found. In 1866 a very perfect skeleton was found in a bog at Cohoes, New York. Many others have been found.

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* A specimen of *Bos latifrons* has been found in Ohio, the *horn-cores* of which were twenty inches around the base and more than seven feet between the points. Between the horn-tips must have been at least ten feet.

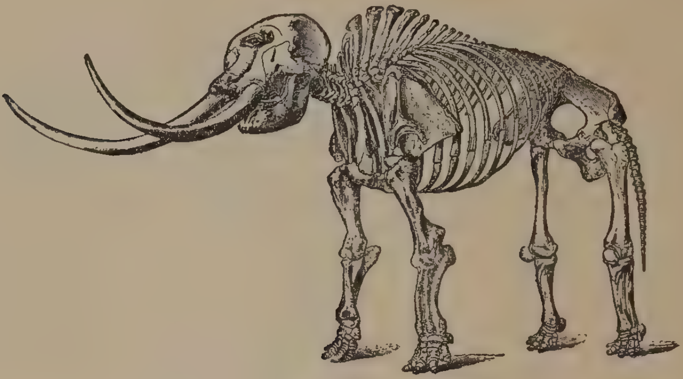

FIG. 966.—Mastodon Americanus, × $\frac{1}{64}$ (after Marsh).

The *Mastodon Americanus* (Fig. 966) is probably the largest land-mammal known, unless we except the Dinotherium (Gaudry). It was twelve to thirteen feet high, and, including the tusks, twenty-four to twenty-five feet long. It differed from the elephant chiefly in the character of its teeth. The difference is seen in Figs. 967, 968, 969. The elephant's tooth, given in Fig. 968, is sixteen inches long, and the grinding surface eight inches by four inches.

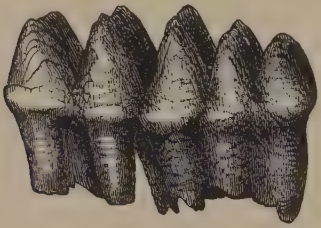

FIG. 967.—Tooth of Mastodon Americanus.

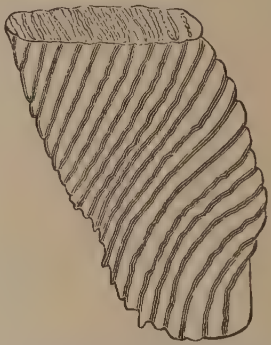

FIG. 968.—Perfect Tooth of an Elephas, found in Stanislaus County, California, $\frac{1}{8}$ natural size.

The two genera of Proboscidians, *Mastodon* and *Elephas*, appeared successively, the one in the later Miocene, the other in early Pliocene, and ranged together through the rest of the Tertiary, the species, of course, changing several times. At the end of the Tertiary, the mastodon became extinct on the Eastern Continent, but continued through the Quaternary, with its companion, the elephant, in America. At the end of the Quaternary, the mastodon became extinct wholly, and the elephant in America and Europe, though it still continues in Asia and Africa. During the Quaternary, therefore, one species of mastodon and two species of elephant roamed in herds over North America from the Gulf to arctic regions. Of the two species of elephant, however, the *primigenius* was mostly confined to the higher latitudes, and the *Americanus* to the southern portions. The latter is distinguished from the former by less crowded enamel plates in the grinders and less curved tusks. According to Cope, about fifty species of Proboscidians are known. Of these five are Dinotheres, twenty-five Mastodons, six Elephants, and five of uncertain place.

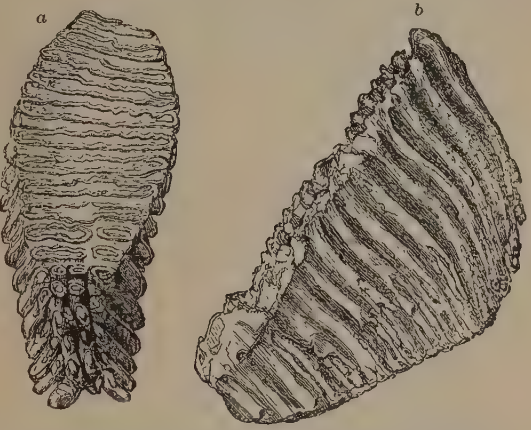

Fig. 969.—Molar Tooth of Mammoth (Elephas primigenius): *a*, grinding surface; *b*, side view, showing the roots (after Lyell).

Genesis of Proboscidians.—The origin of this remarkable order is obscure. It probably branched off in early Tertiary from some generalized form, like Coryphodon or perhaps Pyrothere, but was not well declared until the Miocene. It is well to observe, however, that of the three known genera the order of introduction was: 1. Dinothere; 2. Mastodon; 3. Elephas. Now this is also the order of increasing specialization, especially in complexity of the structure of the molars, and in the size and complexity of the brain. The order of appearance and of extinction of these three forms are shown in diagram (Fig. 970).

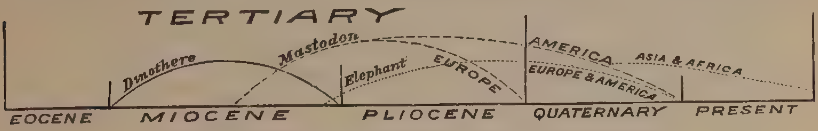

Fig. 970.—Diagram showing Distribution in Time of Proboscidians.

Among *Edentates*, a Megatherium, a Megalonyx, and several Mylodons have been found in North America; but, as their prin-

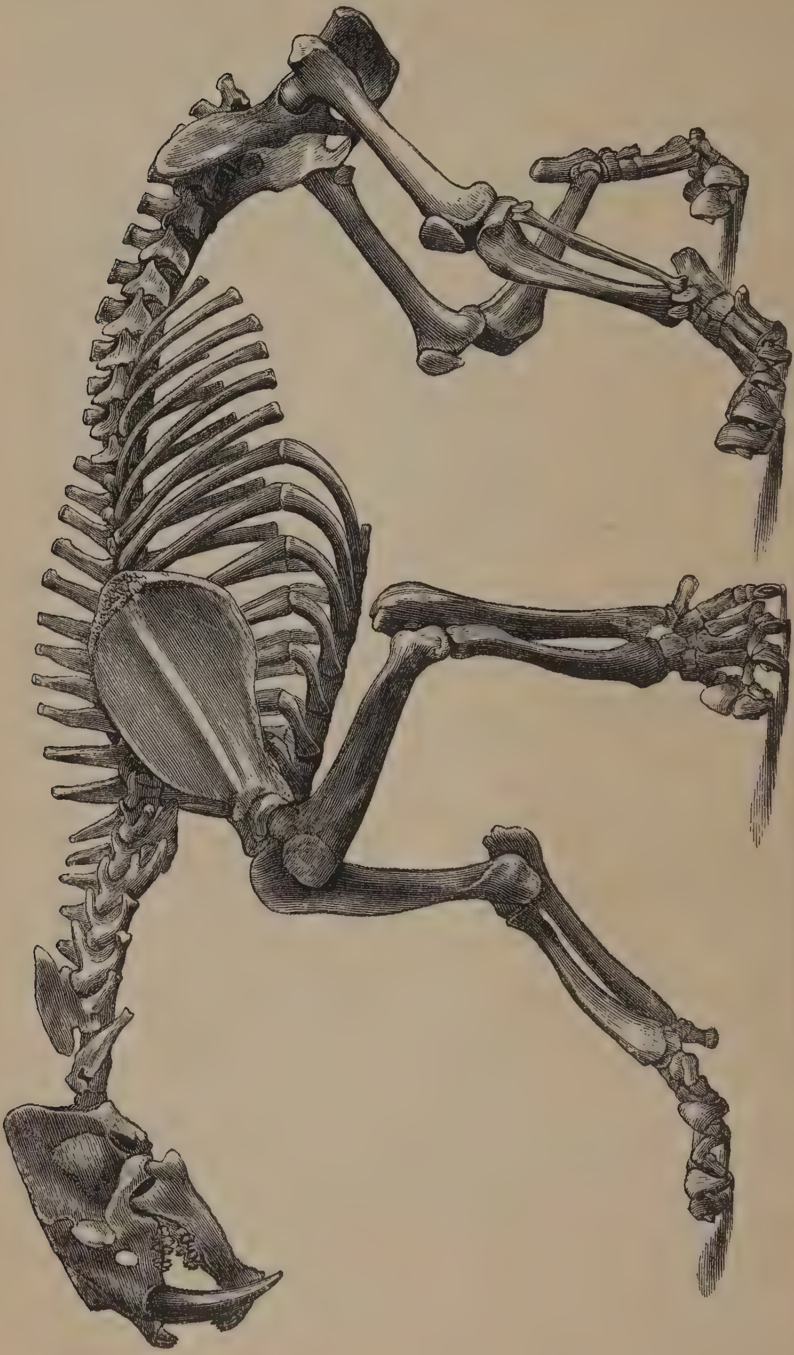

FIG. 971.—Machærodus (Smilodon) necator, complete Skeleton, × $\frac{1}{10}$ (after Burmeister).

cipal home was in South America, we will describe them under that head.

River-Gravels.—In many portions of the United States, but especially in California, remains of mastodon and elephant, and bison, etc., are found in great numbers in river-gravels. The river-gravels of California are spoken of again further on.

Quaternary in South America.—A large number (235) of species of mammals have been found in the soil of the pampas and in the caves of Brazil, far more than live there at present (Zittell). They are mastodons (different species from the North American), llamas, horses, tapirs, rodents, many species of panther-like carnivores, large saber-toothed tigers (*Machairodus neogœus* and *necator*), with curved, saber-like tusks twelve inches long and eight inches beyond the gums (Fig. 971), and especially a large number of Edentates allied to the sloths and armadillos, but of gigantic size.

Of the Edentates, the most remarkable, in fact, one of the most remarkable animals which have ever existed, is the *Megatherium* (great beast) *Cuvieri.* The genus Megatherium ranged in Quaternary times through South America, and into North America, as far as the shores of Georgia and South Carolina. At the mouth of the Savannah River the remains of several individuals of a species of this genus (*M. mirabilis*) have been found. But the largest species and the most perfect specimens have been found in South America.

The *Megatherium Cuvieri*, of which we give a figure (Fig. 972), was larger than a rhinoceros, but was still more remarkable for the clumsy massiveness of its skeleton than for its size. This is especially true of its hind-legs, hip-bones, and tail. For this reason, it is supposed to have been able to stand on its hind-legs and tail, while it used its long free-moving arms, terminated with hands a yard long, to tear down

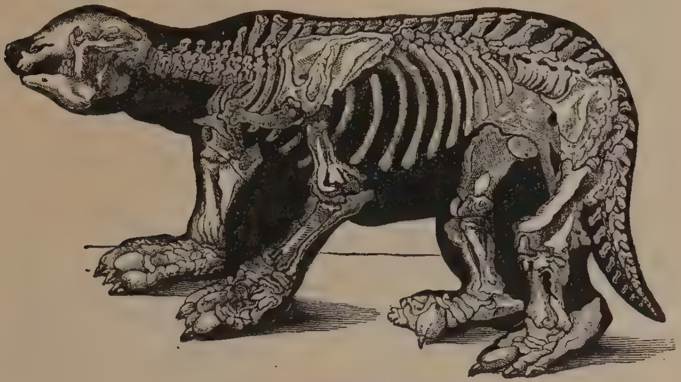

Fig. 972.—Megatherium Cuvieri.

branches on which it fed. The great skeleton represented above is eighteen feet long, and its thigh-bones are three times as thick as those of an elephant. The grinding surface of its molar teeth (it had no others) is traversed by triangular ridges admirably adapted to triturate its coarse food.

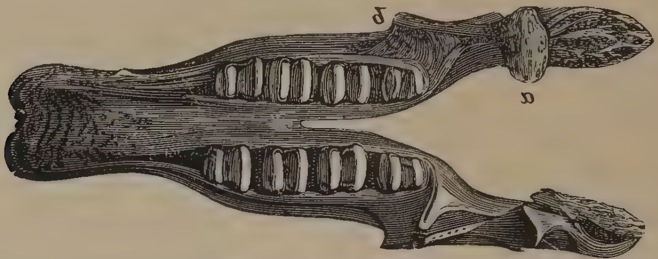

FIG. 973.—Lower Jaw of a Megatherium, showing the Gradual Surface of the Teeth (after Owen).

Megalonyx (big claw) (Fig. 974) is the name of another genus of these gigantic sloths, and *Mylodon* of a third. Both of these genera extended into North America. In fact, the Megalonyx was first dis-

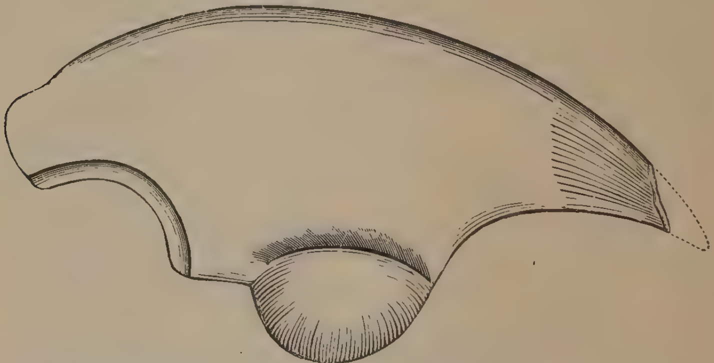

FIG. 974.—Claw-Core of a Megalonyx, × ½ (drawn from a cast of the original).

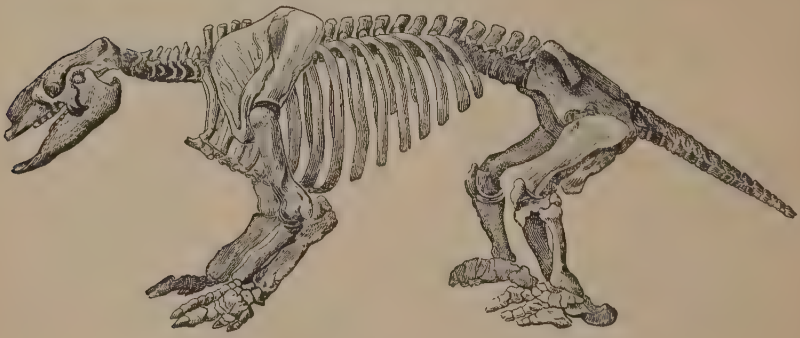

FIG. 975.—Sceledotherium leptocephalus, × $\frac{1}{24}$ (after Boule).

covered in Greenbrier County, Virginia, and named Megalonyx by Thomas Jefferson. The larger species of Mylodon and Megalonyx were about the size of a buffalo, or larger, and Scelidothere (Fig. 975) still larger. These gigantic animals, though allied to sloths, were of course not tree-climbers like modern sloths. They have been well called *Ground Sloths.*

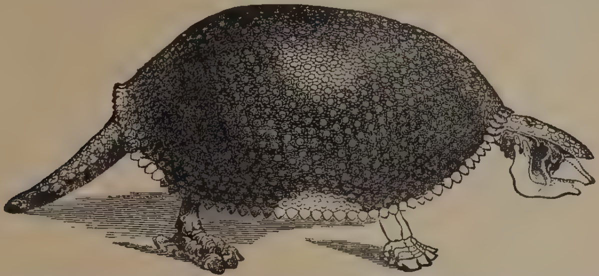
FIG. 976.—Skeleton of Glyptodon clavipes, × $\frac{1}{30}$, Quaternary, South America.

Of the *Armadillos* or *mailed Edentates*, there were several of gigantic size belonging to the genera *Glyptodon*, *Chlamydotherium*, and *Pachytherium*. The accompanying cut represents one of these eight feet long, with an invulnerable coat of mail. Some species of the genus *Chlamydotherium* were much larger—one as big as a rhinoceros, and of *Pachytherium* as big as an ox (Dana).

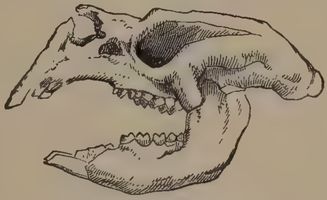
FIG. 977.—Skull of Diprotodon Australis, × $\frac{1}{20}$, Post-Pliocene, Australia.

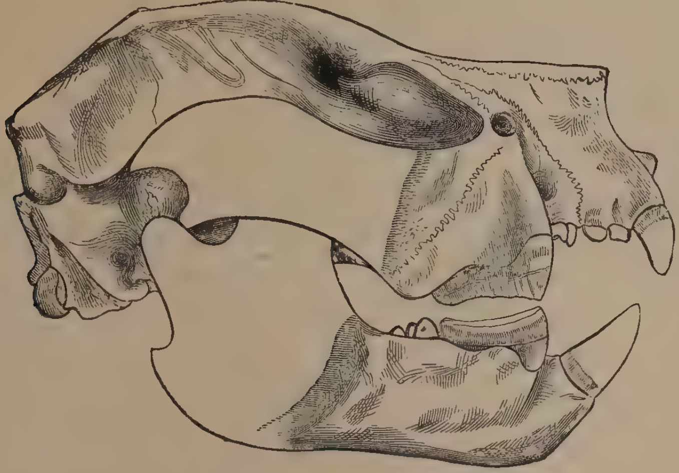
FIG. 978.—Thylacoleo, Skull reduced (after Flower).

Australia.—In Australian caves, also, great abundance of remains has been found, and they show the same prevalence of gigantic species. As *now*, so *then*, the mammals of Australia were almost all *Marsupials*, but the present species are dwarfs in comparison. The largest of these was the *Diprotodon* (two front teeth), a pachydermoid kangaroo as big as a rhinoceros. A reduced figure of the skull, which was three feet long, is given herewith.

Among other remarkable species of marsupials were *Macropus* (kangaroo) *Titan* and *M. Atlas*, of great size; *Nototherium Mitchelli*, as large as a bullock, and a very remarkable species, supposed by Owen to have been carnivorous, and therefore called *Thylacoleo* (pouched lion) *carnifex*, as large as a lion. The striking peculiarity of this animal was the existence of a broad trenchant premolar, as shown in Fig. 978.

Geographical Faunas of Quaternary Times.—We observe, then, that already the geographical distribution of families was similar to that which we find at present. Then, as now, Herbivores greatly predominated in America, while Carnivores were very abundant, and of great size, in the Eastern Continent. Then, as now, sloths and armadillos and llamas characterized the fauna of South America, while Marsupials characterized that of Australia. But in each locality the animal life seems to have been then more abundant, and the species gigantic. According to Zittell, there were three great centers of origin and dispersion of the present mammalian species—viz., *Australia*, *South America*, and *Arctogæa* or Holarctica—i. e., North America and Eurasia north of Sahara and the Himalayas.

Some General Observations on the Whole Quaternary.

1. **Cause of the Climate.**—This is confessedly one of the most difficult questions in geology. There seems to be no doubt that during the Quaternary there were wide-spread oscillations of the earth's crust in high-latitude regions, and a *general* coincidence of climatic changes with these oscillations. Furthermore, there is little doubt that the cold and the ice-accumulation were attended with northern elevation, and the moderation of temperature and melting of the ice, with subsidence in the same region. But there are some reasons for thinking that the coincidence of the climatic changes with the crust-oscillations was *not exact;* that in many places, at least, the maximum of ice-accumulation was *associated with subsidence.* On this point there has been much confusion and difference of opinion. It seems to us that the differences may be reconciled and the facts well explained by supposing that northern elevation produced ice-accumulation; ice-accumulation by weight produced subsidence; subsidence produced moderation of temperature and melting of ice, and this last by lightening of load produced re-elevation. But (and this is the important point) the *effects*

in each case lagged greatly behind the cause. This is well known to be true *in all cases of accumulated effects*, but in this case the lagging is great. On this view the accompanying diagram (Fig. 979) graphically

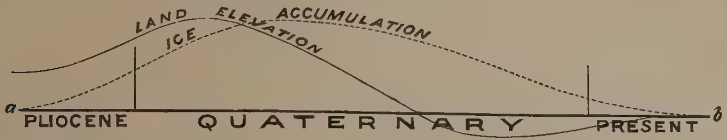

FIG. 979.—Diagram showing the Relation of Land Elevation and Ice Accumulation. The line *a b*, course of time, and also the present condition as to elevation and ice.

represents the facts.* It is seen that, at the time of maximum ice, the subsidence had already commenced. To this lagging of effects, on account of their self-perpetuation and consequent accumulation, must be *added* another cause of *apparent subsidence*, viz., the gravitative attraction of the ice-sheet on the sea, drawing it northward and raising its level.

As to the *cause of the cold*, it is certain that northern elevation would produce cold, and depression a moderation of temperature in the regions thus affected. It is possible, also, that in the case of North America and Europe the chilling effect of elevation was greatly increased by coincident and probably correlative *subsidence of Central America*, by which the *Gulf Stream was diverted across the Isthmus* into the Pacific, thereby depriving the North Atlantic of the warming influence of this stream; or else the broad connection of North America and Europe in high latitude regions, by limitation of the northward extension of the Gulf Stream, as suggested by Dana, would still further chill the northern land of both continents, and at the same time *furnish abundant vapors to be carried northward and condensed as snow.* It is safe to conclude, therefore, that these geographical changes were certainly *one* cause and probably the *main cause* of the rigorous climate of high latitude regions in America and Europe. Thus, when we remember (1) the tendency of cold to perpetuate itself by ice-accumulation, (2) the influence of the Gulf Stream already explained, (3) that the degree of cold necessary is not so excessive as many suppose, 8° to 10° additional being quite sufficient, and (4) that the antarctic ice-sheet is now probably as large and as thick as the northern ice-sheet of glacial times, geographic causes alone will seem quite sufficient. Meanwhile, we may imagine that other regions, especially tropical regions, were as warm as now.

But admitting that increase in the *area* and height of polar lands would increase the rigor of the climate, and decrease of area and height of polar lands would moderate the climate of northern regions, and that the *amount* of this effect it is difficult to estimate—yet the *effect* was so enormous and so wide-spread that the *cause*, even when supplemented by changes in the course of oceanic currents such as the Gulf Stream, has seemed to most physicists and geologists to be *insufficient*. They have cast about, therefore, for some other possible cause, external to the earth itself—i. e., cosmical cause—to explain it.

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* Bull. Geol. Soc. of Am., vol. ii, p. 329, 1891.

Croll's Theory.—Nearly all theories of this kind are open to the fatal objection that they attempt to account only for the *cold*, while heat is just as necessary as cold. As, in a distilling apparatus, a boiler is the necessary complement of a condenser, so for a Glacial epoch excessive evaporation by heat is the necessary condition of excessive condensation of snow by cold. What we want, therefore, is great difference of temperature between summer and winter, and between equator and poles. The only theory which meets this objection, and which is therefore entitled to serious attention, is that of Mr. Croll (embraced also by Geikie and many other English geologists), which attributes it to the *combined influence of precession of the equinoxes and secular changes in the eccentricity of the earth's orbit.* By the former—viz., *precession*—winter, which in the northern hemisphere occurs now when the earth is nearest the sun (perihelion), is gradually in 10,500 years brought round so as to occur when the earth is farthest off from the sun (aphelion). The effect of this, it is claimed, would be to make longer and colder winters, and shorter but hotter summers in the northern hemisphere, such as occur now in antarctic regions. By the latter—viz., *increasing eccentricity* (which forms a much longer cycle)—these effects, which are now small on account of the nearly circular form of the earth's orbit, would become very great. At the time of greatest eccentricity, the earth would be 14,000,000 miles farther off from the sun in winter than in summer, the winters would be twenty-two days longer and 20° colder, and the summers twenty-two days shorter, but much hotter than now.

Fig. 980 is a diagram representing the effect of precession. In *A* we have the condition as it now exists—i. e., the north pole, N P, is turned away from the sun, *S* (winter), at perihelion, and toward the sun (summer) at aphelion. But the earth, rotating on its axis like a spinning-top, does not maintain the same position of its axis—does not sleep in its spinning—but wabbles on its center, the ends of the axis describing a small circle (as shown by the dotted line) in 21,000 years.* In 10,500 years, therefore, the axis will be tilted the other way, so that *B* represents the condition of things at that time. It is seen that winter (north pole turned away from the sun) will be in aphelion, and summer (north pole turned toward the sun) in perihelion. Now, according to Croll, the coincidence of aphelion winter,

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* The cycle of precession is 26,000 years, but the advance movement of the major axis of the orbit makes the cycle of aphelion winter 21,000 years.

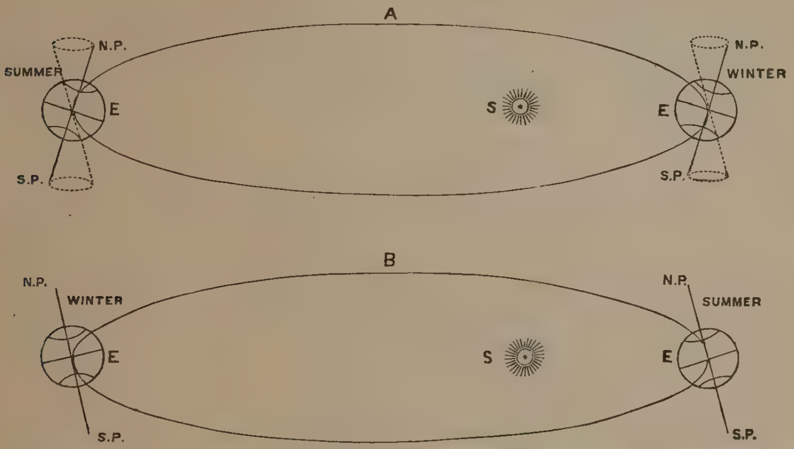

FIG. 980.—Diagram showing effect of Precession: *A*, condition of things now; *B*, as it will be 10,500 years hence. The eccentricity is of course greatly exaggerated.

with a period of greatest eccentricity, produces a glacial climate. The cycle of aphelion winter, as already said, is 21,000 years, that of greatest eccentricity is much longer and far less regular.

Again, these effects, Croll thinks, would be still further increased by changes in the direction of oceanic currents. During aphelion winter in the northern hemisphere the *equator of heat* would be *south* of the geographical equator instead of north of it, as at present. The equatorial current of the Atlantic (p. 40), instead of turning northward to form the Gulf Stream, would be turned southward by the wedge-shaped eastern point of South America, and the northern hemisphere would be still further chilled by the withdrawal of this great moderator of northern climates. Finally, to all these effects must now be added the important effect of the *extreme range of temperature* during an aphelion-winter period, especially at a time of maximum eccentricity. McGee * has shown that the effect of *increased range* is to diminish the mean temperature; while Hill † has shown that it increases the *mean evaporation*, and therefore the mean precipitation, as snow.

If this theory be true, one corollary is the recurrence of Glacial epochs many times in the history of the earth. Another, according to Croll, is the alternation of colder and warmer periods many times during every period of greatest eccentricity, and a similar alternation of each between the two poles, so that the cold period at one pole corresponds with the warm period at the other. Of alternations of colder and warmer periods during the Glacial epoch there are many evidences both in Europe and America, but there is no evidence that these were so numerous (seven or eight) as the theory requires. Of the recurrence of many Glacial epochs in the history of the earth there is as yet no reliable evidence, but much evidence to the contrary. It is true that what seem to be Glacial drifts with scored bowlders, etc., have been found on several geological horizons, but these are usually in the vicinity of lofty mountains, and are probably, therefore, evidences of *local* glaciation, not of a *Glacial epoch.* On the other hand, all the evidence derived from fossils plainly indicates warm climates even in polar regions during all geological periods until the Quaternary. The evidence at present, therefore, is overwhelmingly in favor of the *uniqueness* of the Glacial epoch, unless the Permian be an exception. This fact is the great objection to Croll's theory.

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* American Journal, vol. xxii, p. 437, 1881.

† Geological Magazine, vol. viii, p. 481, 1881.

Mr. Wallace has attempted to remove this objection by modifying Croll's theory. He substantially accepts Croll's view, but thinks that astronomical changes alone will not produce a Glacial epoch, but must be coincident with geographical changes favoring the same result. He maintains that, until the Quaternary, geographical conditions favored warm, uniform climates, especially by several open current-ways from tropical to polar seas, notably one from the Indian Ocean through Western Asia; and that at the beginning of the Quaternary these warm currents were cut off by northern elevation, which we know occurred at this time, while the elevation itself would tend still further to increase the cold. The Glacial epoch was therefore the result of several causes, astronomical and geographical, viz., aphelion winter, maximum eccentricity, and northern elevation. On this view it is easy to see why there should have been but one Glacial epoch.

Furthermore, Mr. Wallace thinks that, during a period of maximum eccentricity, the great accumulation of ice, once effected, would tend to self-perpetuation, i. e., would conserve the cold and tide over the shorter precessional cycles, so that these would have but little effect, and hence there would not be, and in fact were not, seven or eight alternations of cold and hot periods during the Glacial epoch, as Croll thinks. There was but one interglacial period, and this was determined by changes in eccentricity, as seen in Fig. 981.

Mr. Wallace has certainly put the astronomic theory in its best form, and his view may be regarded as not improbable if we admit that among his concurring causes the geographical are the most important. Further, it must be said that while it is probable that astronomical conditions many concur to increase geographical causes, yet physicists are by no means agreed as to what particular conditions would produce this effect.

2. **Time involved in the Quaternary Period.**—If we accept Croll's and Wallace's view, then it is possible to estimate with accuracy the length of the Glacial epoch and the time elapsed since its close, for it is needless to say that astronomical cycles are calculable with great certainty. The following diagram, taken from Mr. Wallace, shows the degrees of eccentricity during the last 300,000 years, and the recurring cycles of precession during that period. If, as he thinks, the cold was mainly due to eccentricity and geographical changes, the precessional changes having little effect, then this figure will also represent the degrees of cold. It is seen that, according to Croll and Wallace, the Glacial period commenced 240,000 years ago, lasted 160,000 years, and 80,000 years have elapsed since its decline. It is seen also that Mr. Wallace makes but one interglacial period instead of eight, the effect of the shorter precessional cycles being tided over by the effect of the accumulated ice.

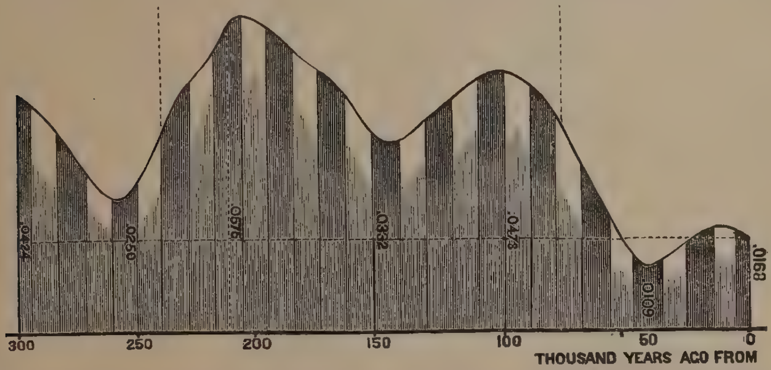

FIG. 981.—Diagram of Eccentricity and Precession: Absciss represents time, and ordinates, degrees of eccentricity and also of cold. The dark and light shades show the warmer and colder winters, and therefore indicate each 10,500 years, the whole representing a period of 300,000 years.

On any view as to the cause of the glacial climate, there can be no doubt that the changes which produced it were effected very slowly, and therefore involved long periods of time, so slowly that they would probably be unobserved by contemporaneous man, if such existed. There are changes by elevation and depression now going on in various parts of the earth which are probably as rapid as those of the Glacial and Champlain epochs. The shores of the Baltic and of Norway are now rising at an average rate of two and a half feet per century. Continue this rate for 800 centuries, and Norway would attain an elevation as great as that of the Glacial epoch, and, if such elevation produces cold, would be again *ice-sheeted.* Depression at a similar rate for the same time would bring about a condition similar to that of the Champlain epoch.. Yet these changes are unremarked, except by the eye of Science. The only difference, if any, between what is in progress now and what took place in glacial times, is the comparative *universality* of the oscillations *then*, and especially their coincidence with certain astronomical changes, which greatly increased their effect upon climate.

Other and more direct methods of estimation, however, such as the recession of waterfalls (p. 15) and of lake-shores (p. 35) and the extreme freshness of glacial scorings and polishings, seem to indicate a much shorter time since the disappearance of the ice-sheet. This is again a strong reason for believing that geographical changes were the main cause of the climate.

Geological Climates.—This seems the proper place to say something of geological climates in general. The subject is confessedly a very difficult one, yet there are some things which seem certain: (1) The mean temperature of the earth-surface has been decreasing through all geological times. (2) The surface temperature of all periods before the Cretaceous and Tertiary was so uniformly distributed that there is little or no evidence of temperature-zones such as we have now. (3) There have been from time to time at uncertain intervals periods of greatly reduced temperature over large portions of the earth's surface. The most certain of these is the Glacial epoch, and next to this the Permian, especially in the Southern Hemisphere. But there is some evidence of the same at the end of Cretaceous. In other words, they seem to be coincident with the critical periods. These are the facts. We explain them as follows:

Explanation.—1. *Decrease of Temperature.*—This is probably due (*a*) to secular cooling from primal incandescence, and (*b*) to decrease of the heat of the sun. The sun is certainly a waning star. It has passed its prime of heat, for it is no longer a white star. (*c*) The gradual changes in the composition of the atmosphere, as shown on page 422, would tend in the same direction.

2. *Uniformity.*—We would attribute this mainly to the composition of the atmosphere, i. e., to the excess in early times of CO_2 and vapor of water. If the watery vapor was transparent, it would tend not only to uniformity, but also to increase of mean temperature by trapping sun-heat, as already explained (pp. 395 and 396). If, on the contrary, the vapor was partially condensed as *haze* or *clouds* it would tend to diminish the extreme heat, and at the same time increase the uniformity.

3. *Periods of Cold.*—This we have already explained, in connection with one such period, viz., the Glacial, as due mainly to high latitude elevation, although astronomical conditions may, and probably do, concur to increase the effect. In the Permian it was mainly in the Southern Hemisphere; in the Glacial in both hemispheres. On this

view we may represent both the general law and the partial uniqueness of the Glacial epoch as follows: Let *AB* represent the course of geological

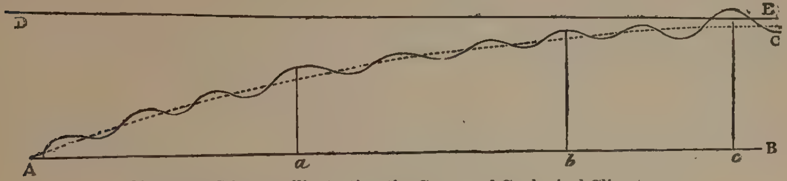

Fig. 982.—Diagram illustrating the Causes of Geological Climates.

time, and the regular ascending dotted curve *AC* the gradual cooling of the surface by all causes known and unknown. Further, let the waving line represent the local oscillations of temperature, and *a*, *b*, *c* the times of greater and more general changes, or critical periods. Finally, let the line *DE* represent such a degree of cold as is necessary to produce glacial conditions at sea-level in middle latitude regions. It is seen that although there are many oscillations of temperature and some greater at critical periods, yet only *once*, at *c*, is the line of glacial conditions reached. This was due partly to the gradual decrease of mean temperature and partly to concurrence of several causes both geographical and astronomical.

3. **The Quaternary a Period of Revolution—a Transition between the Cenozoic and the Psychozoic Eras.**—We have already seen (pp. 293 and 305) that between the great eras, and perhaps also at other times, there have been periods of *oscillation* of the earth's crust, and therefore of changes of *physical geography*, marked by unconformity of strata; and of changes of *climate*, marked by apparently abrupt changes of species. These have been the *critical* periods of the earth's history—periods of revolution and rapid change. But for that very reason they are also periods of *lost records*. We have already also spoken of the lost interval at the end of the Archæan, evidently the greatest of all; again, of a lost interval at the end of the Palæozoic, partly recovered in the Permian, evidently the next greatest; again, of a lost interval at the end of the Cretaceous, in a large measure recovered in the Laramie beds. There are doubtless many others of less extent. These periods are always marked by unconformity of the strata and change in the life-system. The old geologists regarded these changes as sudden and cataclysmic. All geologists now regard the suddenness as largely apparent, and the result of *lost record*.

Now, the *Quaternary is also a critical period*. It corresponds with one of the lost intervals; only in this case, on account of its nearness to us, the record has been recovered. By the study of this period, therefore, we may hope to solve many problems which have heretofore puzzled us. Here, for example, we have oscillations of the crust on a grand scale, producing great changes of physical geography and climate, and therefore of fauna and flora. Here we have wide-spread unconformity of present sediments on eroded surfaces of all previous strata, over the whole sea-bottom as far as the submerged continental margin, and, if the antarctic continent was connected with South America, South Africa, and Australia, also over the whole antarctic ocean bottom. If we add to this the universal unconformity of the drift on the eroded rock of all other ages, we have an unconformity as extensive as any known. But we observe that in this case these effects have been produced slowly, and that the fauna and flora have *not* been suddenly destroyed and suddenly recreated, but have continued to live throughout, the species gradually changing. But, what is still more interesting, much light is thrown also on the hitherto insoluble problem of the mode and the cause of the comparatively rapid change of species in these critical periods. The attentive study of the Quaternary shows that, in addition to the direct effect of change of climate, one great cause of change of species has been *migration:* migration north and south, *enforced* by change of temperature; migration in any direction, *permitted* by change of physical geography. This point is so important, that we must explain it somewhat fully.

It will be remembered (p. 526) that in Miocene times Greenland, Iceland, and Spitzbergen were covered with a luxuriant, temperate vegetation. The congeners of the vegetation of that time are found now in California, along the shores of the Southern Atlantic States, and in Southern Europe. Evidently at that time there was *no polar ice-cap*, and therefore no *arctic plants.* At the end of the Pliocene, the vegetation shows a climate not greatly differing from the present. It is probable, therefore, that the cold had increased until an ice-cap had formed, such as now exists in polar regions, with its accompaniment of arctic species. As the Glacial epoch came on and culminated, the polar ice slowly extended—its margin crept slowly southward, until it reached 40° in America and 50° in Europe, with local extensions stretching still farther southward, in mountain regions. The southern polar regions were probably similarly affected, either simultaneously or alternately.

We must not confound this movement southward of the southern limit of the ice with the *current motion* of the ice-sheet itself. The limit of the ice-cap is like the lower limit of a glacier (p. 48). It may be stationary, or advancing or retreating, but the glacial stream flows ever onward. Again, the motion of a glacial current is slow—perhaps one to three feet *per day*—but the extension or recession of the glacial limit may be far slower, perhaps a few feet *per annum.* We may thus easily appreciate the immense time necessary to advance this limit of the ice-cap to 40° latitude.

At the end of the Glacial and the commencement of the Champlain epoch a movement of the ice-limit in a contrary direction—a retreat northward—commenced and continued, with perhaps some alternate progressions and regressions, to its present position.

Now, the effect of this advance and retreat of polar ice upon plants and animals must have been very marked. Temperate plants, inhabiting Greenland in the Miocene, were pushed to the shores of the Gulf. Arctic plants—i. e., those which haunt the margin of perpetual ice—were pushed to Middle United States and to Middle Europe; and arctic shells were similarly driven southward, *slowly*, generation after generation. We say *slowly*, for otherwise they must have been destroyed. With the return of temperate conditions, and the retreat of the ice-cap, these species, both shells and plants, again went northward to their appropriate place. But the plant species, and some land invertebrate species, such as insects, had an alternative which the shells had not, viz., to seek arctic conditions also *upward* on mountains. Many did so and were left stranded there. Thus is explained the remarkable fact that *Alpine* plant-species in Europe are similar to and largely identical with those in America; and both with the present *arctic* species. This indicates a former wide distribution of identical arctic species all over Europe and America, and their subsequent retreat *northward* into polar regions and *upward* into Alpine isolation. Grote has observed a similar isolation of Labrador insect-species on Mount Washington, and on the Colorado mountains.*

There was probably a similar movement, to a less extent, of temperate species. In the Taxodium of the Southern Atlantic and Gulf swamps, and the Sequoias of California, we doubtless have examples of species wide-spread in Miocene times, which have been destroyed by these climatic changes, except in certain limited areas.

But plants and lower species of animals are far less affected by changes in physical conditions than are the higher species of animals. This is shown by the wide range both in space and time of the former as compared with the latter. Under these great changes and enforced migrations, therefore, plants and invertebrate animal species maintained their specific characters mostly unchanged, or but slightly changed. But in the case of mammals destruction or change was inevitable. Both took place—destruction of some and change of the remainder.

In America some time during Quaternary, perhaps during the period of northern subsidence, there was *probably* a broad land-connection of North America with South America by the Caribbean Sea region; and certainly, as shown by the similarity of plants, with Northern Asia by the region between the Aleutian Isles and Bering Strait.

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* American Journal of Science, 1875, vol. x, p. 335.

Thus migrations were not only enforced by climatic changes, but permitted by geographical connections with adjacent continents. Also the great Pliocene lake, 1,000 miles long (p. 523), which separated Western from Eastern North America was abolished, and migrations became freer between the East and West. It is evident that from all these causes mammalian faunas from widely-different regions were precipitated upon each other, and struggled together for mastery. Large numbers of species were destroyed, and the fittest only survived, and these only under changed forms. It is quite possible that man came to America with the Asiatic mammalian invasion. If so, his earliest remains in America may be looked for on the Pacific coast.

Of course we use the word *migrations* in its widest sense, as change of habitat of species as well as of individuals.* In the case of plants and many lower animals, the place of species only moved slowly from generation to generation. In the case of mammals there was more decided movement of individuals.

This very important subject has been more closely studied in Europe than here, although we believe that America is the simplest and best field for its elucidation. During the Quaternary probably at least four distinct mammalian faunas struggled together for mastery on European soil: 1. The Pliocene autochthones. 2. Invasions from Africa, permitted by geographical connection opening a gateway through the Mediterranean, since closed. 3. Invasions from Asia, by opening of a gateway which has remained open ever since; with this invasion probably came man. 4. Invasions from arctic regions. Probably more than one such invasion took place; certainly one occurred during the second Glacial epoch, called on that account the Reindeer period.

The final result of all this struggle was, that the Pliocene autochthones were destroyed or driven southward in Africa; the southern species were mostly destroyed or driven back with changed forms and diminished size; the northern species, reindeer, glutton, etc., retreated again northward, and the Asiatics remained in possession of the field, but greatly changed by the struggle. Man was among these, and certainly one of the principal agents in the change. Speaking more accurately, the present fauna of Europe may be said to be a product of all these factors; but the Asiatic invasion seems to be the largest factor.

Thus, then, the gradual progress of evolution through all geological time, and the causes of the phenomenon of rapid change of species at critical periods of the earth's history, may be briefly summarized as follows:

1. A gradual, *extremely slow* evolution of organic forms under the operation of all the forces and factors of evolution known and un-

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* The term *dispersal* is often used.

known, whatever we may conceive these to be. This cause acting alone would produce gradual changes in time (geological faunas), but without geographical diversity. It would be easy to synchronize strata in different countries, because fossils of the same period would be identical everywhere. But we know this is not true.

2. This slow evolution takes *different directions* in different places and under different physical conditions, and thus gives rise to *geographical faunas and floras.* Such geographical faunas and floras, if isolated by physical barriers, become more and more diverse so long as the barriers are maintained. This cause acting alone would produce extreme geographical diversity, greater than any now known, and render determination of synchronism impossible. This also is not true.

3. During *critical periods physical changes* and consequent *migrations*, partly enforced by changes of climate, partly permitted by removal of barriers, and the precipitation of adjacent faunas and floras upon each other, and the consequent severe struggle for life, give rise to *far more rapid changes of species*, but at the same time to greater *geographical uniformity.* This more rapid change of organic forms is produced partly by *severer pressure of external conditions*, certainly one factor of change; partly by *severer struggle for life*, certainly another factor of change; and partly due to the effect of *new dominant types*, another factor of change; and doubtless partly also to the more active operation of *other factors of change*, which we do not yet understand. These critical periods tend to produce not only more rapid general evolution, but also to destroy extreme geographical diversity; and since it operates on animals rather more than plants, plant species are more apt to be local, and are less certainly carried along with the stream of general evolution, and are therefore less reliable in determining geological age than animals.

4. Re-isolations in new positions. This would again produce divergence of geographical faunas and floras increasing with time, as long as the isolation continued. Thus it is seen that geographical diversity is a product of three factors—viz., *difference of environment*, *isolation*, *and time.*

The last of these critical periods was the Quaternary. Therefore in the changes of physical geography and climate of this period we find the *main cause of the present distribution of species ;* and, conversely, this distribution furnishes the key to the geographical changes and the direction of migrations during the Quaternary.

The principles enumerated above are so important, that some examples illustrating seem necessary.

1. *Australia.*—This one is less dependent on the Glacial period, but is an excellent illustration of the principle. The fauna and flora of Australia are the most peculiar known anywhere. Confining our at-

tention to mammals; of about one hundred and thirty species known in Australia, all except two or three bats and rats* (of all animals the most likely to be accidentally introduced) are *non-placentals*, i. e., *marsupials* and *monotremes.* And, moreover, with the exception of several opossums in America, North and South, non-placentals are not found anywhere except in Australia and neighboring islands. The explanation is as follows: Of all countries, Australia has been the *longest isolated* from all other continents. The wide migrations of the Quaternary which mingled the faunas and floras of other continents did not reach this one. It will be remembered that, in Jurassic times, marsupials in great numbers inhabited Europe and America, and doubtless all other great continents, Australia among the number. It will be remembered also that true placental mammals were not introduced *until the Tertiary.* It is evident, then, that Australia was separated *before the Tertiary*, and has been isolated ever since. The severe struggle which determined the evolution of placentals elsewhere did not affect that continent. Placentals were not evolved there, nor could they get there from abroad.

2. *Africa.*—The mammalian fauna of Africa, south of Sahara, as shown by Wallace (Island Life), consist of two very distinct groups—viz., a group of small animals of very generalized type—insectivores and lemurs; and a group of large, powerful, and highly-specialized animals —carnivores and herbivores. The animals of the former group are peculiar to Africa and Madagascar, and are probably indigenous; the animals of the latter group are similar to the Pliocene animals of Eurasia, and are probably invaders. The explanation is as follows: During late Tertiary times, Africa was separated from Eurasia probably by a sea, and inhabited *only* by the group which we called indigenes. Then came the Glacial oscillations, which opened a gateway into Africa, and the concomitant climatic changes which drove the Eurasian Pliocene animals southward. These invaders soon dominated the weaker indigenes and were subsequently isolated in their new home. The struggle which followed has produced considerable change in both groups, but especially in the indigenes.

3. *Madagascar.*—The mammalian fauna of Madagascar is very remarkable; nearly all the species being peculiar to that island. There is, however, a general resemblance to the indigenes of Africa. The explanation is as follows: During Tertiary times, Madagascar was a part of the African Continent, and both inhabited by the same animals, viz., the indigenes. But in Pliocene times, before the northern invasion, it was separated, and therefore the invasion did not reach it.

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* The dingo or native dog is no exception, because, according to Wallace, it was introduced by man.—Island Life, p. 45.

Meanwhile by long isolation, the Malagasian fauna changed slowly to its present state, but the change was not so great as in their African congeners, who had to bear the brunt of the struggle with invaders. Therefore, we have in the Malagasian fauna a somewhat nearer approach to the Tertiary fauna of both.

4. *British Isles.*—The fauna and flora of the British Isles are almost but not quite identical with those of Europe. Between the two there are strong varietal but not specific differences. They are also somewhat less rich, some species being wanting which are found on the continent. This is especially true of Ireland. The explanation is as follows: The climatic changes of the Glacial epoch, but especially the ice-sheet and subsequent submergence of the Champlain completely destroyed the indigenous species of these islands. But, during the elevation of the second Glacial epoch, they were again broadly connected with the continent, and therefore colonized by continental species. They have been again separated by subsidence, and divergence of organic forms has again commenced; but the period of connection was so brief that the colonization, especially in the extreme parts, was not completed before re-isolation; and the time since re-isolation has been too short for the divergence to go very far; it has reached only varietal differences.

5. *Coast Islands of California.*—Along the coast of the southern part of California there is a string of bold, rocky islands, nearly two thousand feet high, and about fifty miles off shore. The flora of these islands, as shown by Prof. Greene,* is very remarkable. Of nearly three hundred species found there, about fifty are entirely peculiar—being found nowhere else in the world. Of the others, all are characteristic California species. Now for the explanation: During late Tertiary and early Quaternary times the continent was higher than now, and these islands were a part of California. We have already given proof of this fact on page 586. During that time California, including these islands, was occupied by a flora not greatly different from that of the islands now. By the oscillations of the Quaternary the islands were separated. Then came the northern invasion of species, changing some of the native species and destroying others, and forming the California flora of to-day. The islands were spared this invasion by isolation. It is probable, therefore, that in the island flora we have a somewhat near approach to the flora of California before the invasion.†

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* Bulletin of the California Academy of Sciences, No. 7.

† American Journal of Science, vol. xxxiv, p. 457, 1887. This deduction has recently been confirmed by the marine fauna of Santa Catalina. A large percentage of the living species there are extinct on the main coast, being fossils of the Pliocene, and the rest are arctic species.—Jour. Geol., vol. iii, pp. 453 and 487, 1895.

Thus, then, regarding the *Cenozoic* and the *Modern* as consecutive eras, and the Quaternary as the transitional, revolutionary, or critical period between, we see a *great*, and, if we had lost the Quaternary, an apparently *sudden*, change of species. Yet this change, as great as it is, is not to be compared in magnitude with that which separates the great eras or even ages from each other. Evidently, therefore, we must regard the lost interval between the Archæan and Palæozoic, and that between the Palæozoic and Mesozoic, yes, even that between the Mesozoic and Cenozoic (as small as this latter is in comparison with the others), as all of them far greater than the whole Quaternary period; or else the forces of evolution must have been far more active in those earlier times than more recently. But, on the other hand, we must remember that the change *is not yet completed;* that the introduction of man has continued and increased the changes commenced by physical and organic causes. When completed—i. e., when civilized man shall have occupied the whole earth—the change will then be as great as any that has ever occurred in the history of the earth.

4. **Drift in Relation to Gold.**—As already stated (p. 250), gold occurs in two positions, viz., in quartz *veins* intersecting metamorphic slates (quartz-mines) or in river-*gravels* (placer-mines). The auriferous slates may be of various ages. In the Appalachian, the Ural, and in Australia they are metamorphic, Silurian, or Cambrian.* In California they are mainly Jura-Trias. The placer-mines are nearly always late Tertiary or early Quaternary gravels. There has been throughout all geological time a progressive concentration of gold and other metals in more and more available form. 1. It was disseminated in excessively small quantities in the slates—too small to be easily detected—probably derived from the sea, in the waters of which small quantities are detectable. 2. After upheaval, crumpling, metamorphism, and fissuring, it was leached out and accumulated along with silica and metallic sulphides in the fissures, as auriferous veins. 3. Atmospheric agencies acting on the outcropping veins dissolved away the sulphides, leaving the gold *free* and therefore in more available form along the backs of the veins. 4. In the meantime the weathering of the slates on a *low angle of slope*, preceding the Post-Tertiary elevation (page 276), resulted in *deep residual soil*, abundantly mixed with imperishable quartz fragments containing gold. 5. Then came last the rushing waters of latest Tertiary and earliest Quaternary—i. e., after the upheaval commenced—carrying to the sea the finer soil, but accumulating the quartz fragments in the form of pebbles in the river-beds, where they are sorted and panned, leaving the coarser gold high up the slopes and at the bottom of gravels, forming the placers, the richest of all.

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* Pre-Cambrian in Appalachian (Becker).

The placers of California, however, are of two kinds, viz., the ordinary or superficial placers, and the *deep placers*. The superficial placers are gravel-drifts in the present river-beds. The deep placers are gravel-drifts in *old river-beds*. These old river-beds, as already stated (pp. 258, 591), are in many cases covered up with lava. Usually the general direction of the old bed coincides with that of the present river-system, but sometimes the present river-system cuts across the old river-system. In all cases, however, it is evident that the old river-gravels were formed before the lava-flow, and the newer gravels after the lava-flow. In all cases also the present river-system has cut down *far below the old beds*, in this respect entirely different from the old river-beds of the eastern portion of the continent. The reason of this has already been explained (p. 591).

The following figures are ideal sections altered a little from Whitney's: Fig. 983, of a case in which the old and the present river-beds are parallel to each other, and Fig. 984, where the latter cut through the former. In the former case the section is across the lava-flow, as well as across the river-beds; in the latter case it is in the direction of the lava-flow, and therefore of the old river-bed, but across the present river-bed.

In Fig. 983, which is a section across Table Mountain, in Tuolumne County, California, *L* is the lava-cap, 140 feet thick, beneath which is the old river-bed, *R*, with its gravel, *G*, now worked by a tunnel, driven through the *rim-slate S*. More recent gravels, *G′*, are seen in the present river-beds, *R′*. In this locality *G* represents the deep placers, and *G′* the superficial placers.

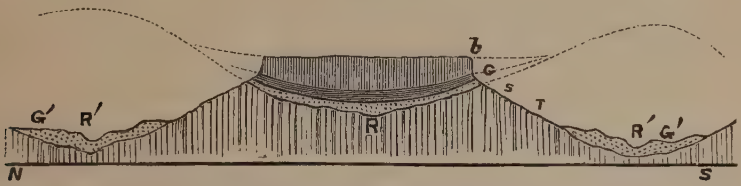

FIG. 983.—Section across Table Mountain, Tuolumne County, California: *L*, lava; *G*, gravel; *S*, slate; *R*, old river-bed; *R′*, present river-bed.

The history of changes shown in these sections is sufficiently obvious. In the time of the old river-system, *R* was a river-bed, doubtless with a ridge on either side represented by the dotted lines. In this bed accumulated gravel, containing gold. Then came the lava-flow, which of course ran down the valley, displacing the river and covering up the gravels. The displaced rivers now ran on either side of the *resistant* lava, and cut out new valleys, 2,000 feet deep, in the solid slate, leaving the old lava-covered river-beds and their auriferous gravels high up on a ridge. The deeper cutting was the result of the higher slope. In other cases the convulsion which ejected the lava also changed greatly the direction of the slope of the country, and therefore the direction of the streams. In such cases of course the present river-system cuts across the old river-beds and gravels, and their covering lavas, as shown in Fig. 984.

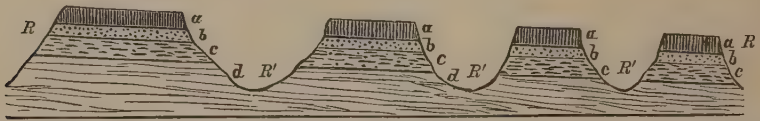

FIG. 984.—Lava-Stream cut through by Rivers: *a a*, basalt; *b b*, volcanic ashes; *c c*, Tertiary; *d d*, Cretaceous rocks; *R R*, direction of the old river-bed; *R′ R′*, sections of the present river-beds (from Whitney).

Age of the River-Gravels.—The age of the old river-gravels is still doubtful; that of the newer river-gravels is undoubtedly Champlain. Below we give a list, taken from Whitney, of the remains found in these gravels:

- Newer placers.
  - Great mastodon.
  - Mammoth.
  - Bison.
  - Tapir, modern.
  - Horse, modern.
  - Man's works.
- Deep placers.
  - Great mastodon.*
  - Mammoth.
  - Mylodon.
  - Tapir, modern.
  - Rhinoceros (ally).
  - Hippopotamus (ally).
  - Camel (ally).
  - Horse, extinct species.

It will be seen that the fauna of the deep placers unite Pliocene and Quaternary characters. The great mastodon, the mammoth, the tapir, and mylodon, are distinctively Quaternary, while the others are Pliocene. The plants, according to Lesquereux, are decidedly Pliocene, or even late Miocene. Therefore Whitney has not only put the deep placers in the Pliocene, but made them the representative of the whole Pliocene, and probably Miocene, and the lava-flow as the dividing-line between the Tertiary and Quaternary. But, all the facts considered, it seems most probable that both the filling of the old river-beds, and their protection by lava, took place comparatively rapidly, and were together the closing scene of the Tertiary drama. The deep gravels, therefore, may be placed indifferently in the late Pliocene or earliest

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* Whitney states (Geological Survey of California, vol. i, p. 252) that neither the mastodon nor the mammoth is found in deep placers; but both have since been found there.

Quaternary. The newer gravels are undoubtedly Quaternary and recent.

In any case, we have here an admirable illustration of the immensity of geological times. The whole work of cutting the hard slate-rock 2,000 feet or more has been done since the lava-flow, and therefore certainly since the beginning of the Quaternary. But it is necessary to remember that, on account of the high slope of the new river-beds, the work was exceptionally rapid.

CHAPTER VI.

PSYCHOZOIC ERA—AGE OF MAN—RECENT EPOCH.

Characteristics.—The Quaternary, and, indeed, all previous ages, were reigns of *brute force* and *animal ferocity*. A condition of things prevailed which was inconsistent with the supremacy of man. The age of man, on the contrary, is characterized by the *reign of mind*. Therefore, as was necessary, the dangerous animals decreased in size and number, and the useful animals and plants were introduced, or else preserved by man.

Distinctness of this Era.—In regard to the distinctness and importance of this era, there are two views which will probably ever divide geologists, depending on the two views regarding the relation of man to Nature. From the purely structural and animal point of view, man is very closely united with the animal kingdom. He has no department of his own, but belongs to the vertebrate department, along with quadrupeds, birds, reptiles, and fishes. He has no class of his own, but belongs to the class Mammalia, along with quadrupeds. Neither has he an order of his own, but belongs to the order of Primates, along with monkeys, lemurs, etc. Even a family of his own, the *Hominidæ*, is grudgingly admitted by some. But from the psychical point of view it is simply impossible to overestimate the space which separates man from all lower things. Man must be set off not only against the animal kingdom, but against the whole of Nature besides, as an equivalent: Nature the *book*—the revelation—and man the *interpreter*.

So in the history of the earth: from one point of view the era of man is not equivalent to an era, nor to an age, nor to a period, nor even to an epoch. But from another point of view it is the equivalent of the whole geological history of the earth besides. For the history of the earth *finds its consummation, and its interpreter, and its significance, in man.*

But there is still another and perhaps a better reason for making this a primary division. There is now going on under our eyes, and by the agency of man, a change of fauna and flora as sweeping, and far more rapid, than any which has ever taken place in the history of the earth. We do not sufficiently appreciate this, only because we are in the midst of it. The change will be completed when civilized man dominates the whole earth.

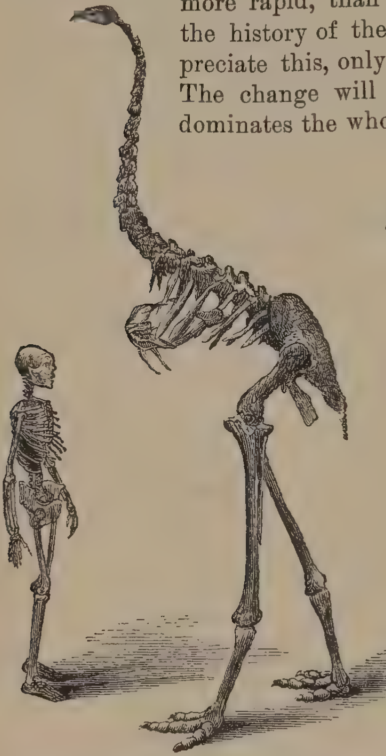

Fig. 985.—Dinornis giganteus, × $\frac{1}{36}$ (from a photograph of a skeleton in Christchurch Museum, New Zealand).

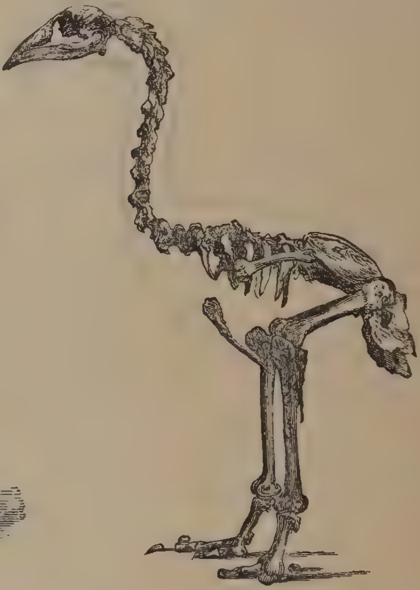

Fig. 986.—Aptornis didiformis, × $\frac{1}{10}$ (from a photograph of a skeleton in Christchurch Museum, New Zealand).

The rocks of this epoch are the present river-deposits, lake-deposits, sea-deposits, volcanic ejections, etc., already treated of in Part I. The *fauna and flora* of this epoch are the species *still living* on the earth. These are different from those of the Tertiary, and largely from those of the Quaternary, times; but the change, as we have already shown, has been gradual, not sudden; man himself being one of the chief agents of change.

The Change still in Progress—Examples of Recently-Extinct Species.—The gradual change of fauna has been going on through many ages, and is still going on under our eyes. Many remarkable Quaternary species have lingered, and become extinct by the agency of man, even in historic times. Among the most remarkable of these are the huge wingless birds, the remains of which have been discovered in New

Zealand, Madagascar, and Mauritius, viz., the *Dinornis* (huge bird), *Æpyornis* (tall bird), *Palapteryx* (old wingless bird), the Solitaire, and the Dodo. Through the kindness of Mr. C. D. Voy, I am able to give good figures of the skeletons of several of these extraordinary extinct birds, taken from photographs (Figs. 985–987).

The *Dinornis giganteus* of New Zealand, and the *Æpiornis* of Madagascar, were probably twelve feet high. The tibia of the former has been found nearly a yard long, and as thick as the tibia of a horse, and the egg of the latter, well preserved, thirteen inches long and nine inches in diameter, with a capacity of two gallons. The toe-bones of the *D. elephantopus* (Fig. 987) rivaled in size those of the elephant (Owen). These huge birds must have been capable of making tracks nearly as large as those of the supposed birds of the Connecticut Valley sandstone (p. 471). Such tracks have indeed been recently found in New Zealand, in a very soft sandstone. The Dodo, of Mauritius, a heavy, clumsy bird, of fifty pounds' weight, with loose, downy feathers, and imperfect wings, like a new-born chicken, became extinct only about a hundred and fifty or two hundred years ago. The *Apteryx*, to which of all living birds the *Dinornis*, *Aptornis*, etc., are most nearly allied, still survives, ready to disappear (Fig. 988).

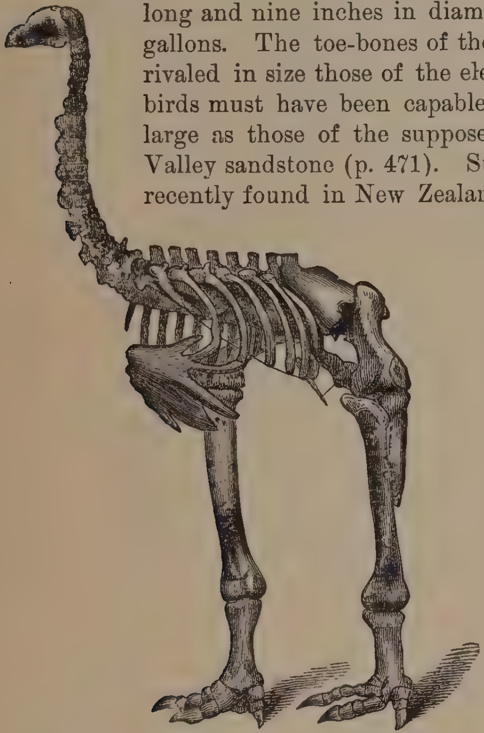

Fig. 987.—Dinornis elephantopus, × $\frac{1}{18}$ (after Owen).

The *Bos primigenius*, the gigantic ox of Quaternary times, is supposed to be the same as the *Urus* of Cæsar, and therefore became extinct since Roman times. The Quaternary bison of Europe would have been now entirely extinct but for the imperial edict which preserves a few in the forests of Lithuania. The lion, the tiger, the bison, the elephant, and the rhinoceros, and, in fact, all the fiercer and larger animals, are even now disappearing before the advance of civilized man.

Thus, in passing from geological to present times we trace rocks into sediments and soils; geological agencies into chemical and physical agencies, now in operation; extinct faunas and floras into the living fauna and flora; in a word, geology into chemistry and physics, and paleontology into zoölogy and botany.

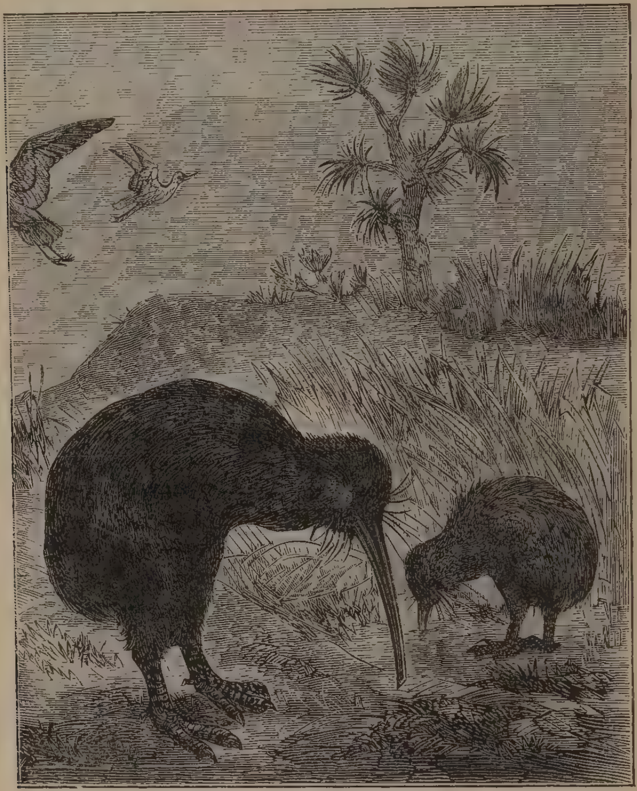

Fig. 988.—Apteryx Australis.

Now, in this gradual change of fauna, *when* did man first appear upon the scene, and *what was the character* of primeval man? This introduces us to two very important but very difficult and obscure subjects.

I.—Antiquity of Man.

On this interesting subject the three sciences—History, Archæology, and Geology—meet and co-operate; and the recent rapid advance has been the result of this union, and especially of the application of geological methods of research.

Archæologists have long ago divided the history of human civilization into three epochs or *ages*, named, from the materials of which weapons and tools are made, respectively the *Stone age*, the *Bronze* *age*, and the *Iron age.* We are here concerned only with the *Stone* age; the others belong to history.

Closer study has again divided the Stone age into two, viz., the *Palæolithic* (old Stone age) and the *Neolithic* (newer Stone age). During the former, only *chipped* stone implements were used; while in the latter *polished* stone implements were *also* used. It is principally with the *Palæolithic* that we are here concerned.

Still closer study, in connection with geology, has again divided the Palæolithic into an earlier and a later. The earlier, being contemporaneous with the mammoth, is called the *Mammoth age;* and the latter, for similar reasons, the *Reindeer age.* The mammoth, however, existed also in this latter age. The former seems to correspond with the Champlain or, perhaps, interglacial epoch in geology, for these are often confounded, and the latter with the Second Glacial epoch passing into the recent epoch. The Neolithic commences the Psychozoic era, or *reign of man*—the period when *man had established his supremacy.* The following table expresses these views:

3. Iron age.	Historic		Psychozoic era.
2. Bronze age.			
1. Stone age.	Neolithic—Domestic animals.		
	Palæolithic.	Reindeer age	= Second Glacial or early recent epoch.
		Mammoth age	= Champlain epoch or perhaps interglacial.

These divisions and their relation to geological epochs have been established *in Europe.* They would probably apply also to some parts of Asia and Africa, for in portions of these old countries man has doubtless passed, successively and slowly, through all these stages. But all these stages are not represented in all countries, nor do they necessarily correspond to the geological epochs mentioned above. The South-Sea-Islanders, for example, are still in the Stone age. The American Indians were in the Stone age only three centuries ago.

The table given above carries man back to the Champlain or even the interglacial epoch. There are some geologists who think they find evidence of a much earlier existence of man. We will, therefore, very rapidly review the evidences of the antiquity of man. In doing so, however, we shall accept none but thoroughly reliable evidence. There has been recently far too much eagerness to find facts which overthrow accepted beliefs, and to accept them on this account alone. We will take up European localities first, because the subject has been more carefully studied there.

Primeval Man in Europe.

Supposed Miocene Man—Evidence unreliable.—The earliest period in the strata of which any supposed evidences of the existence of man have been found is the *Miocene.* These evidences, however, are confessedly meager, and by all careful investigators considered unreliable. Some flint-flakes (Fig. 989), so rough that they may be the result of physical instead of intelligent agencies; some bones of animals, marked with parallel scratches, as if *scraped*, but the scratches may have been produced by currents, or, as Lyell thinks, by the teeth of Rodents; some more positive evidences of man's agency, but in strata of doubtful age, or else the result of accidental mixture not contemporaneous with the deposit itself—such is, in brief, the evidence. The Miocene man is not acknowledged by a single careful geologist. Mortillet thinks that there may have existed in Miocene times a tool-making animal, but not true man.

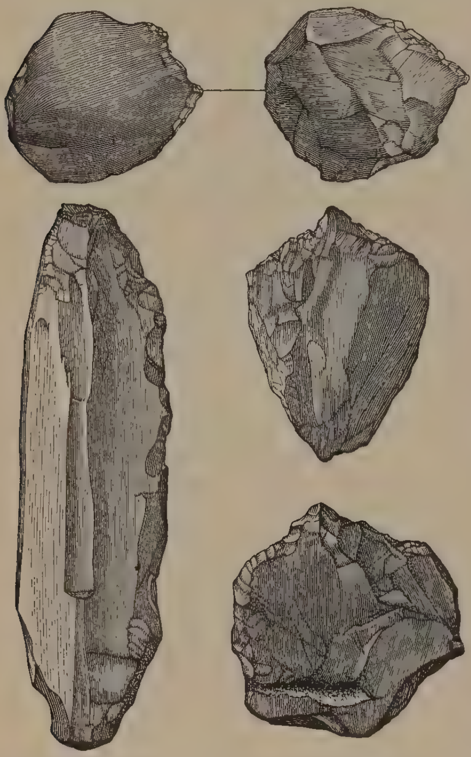

Fig. 989.—Flint Flakes collected by Abbé Bourgeois from Miocene Strata at Thenay (after Gaudry). Natural size.

Supposed Pliocene Man.—The evidence of the existence of man in Europe during the Pliocene period is, if possible, still more meager and unreliable. M. Hamy thinks he has found undoubted evidence of human agency in flint implements in Pliocene strata at Savone; but the contemporaneousness of the flints and the deposit is regarded as doubtful. Again, Palæolithic implements have been found in Madras in strata supposed by Falconer to be Pliocene; but more recent investigations make the strata Quaternary.[*] Of the supposed Pliocene man in California we will speak further on. Suffice it to say that Dawkins, summing up the evidence in 1882,[†] Boule in 1888,[‡] and Evans in 1890,[#] decide that the existence of Tertiary man is yet unproved.

Quaternary Man—Mammoth Age.—But of the existence of man in Europe and America, as early as the middle of the Quaternary period, there seems to be abundant evidence. We shall select only a few striking examples:

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[*] American Journal of Science, 1875, vol. x, p. 232.

[†] Nature, vol. xxvi, p. 434.

[‡] Revue d'Anthropologie, vol. iii, p. 679.

[#] Nature, vol. xlii, p. 508, 1890.

a. **In River-Gravels.**—In the terraces of the river Somme, near Abbeville, were found, nearly forty years ago, by M. Boucher de Perthes, chipped flint implements, associated with bones of the mammoth, rhinoceros, hippopotamus, hyena, horse, etc. The doubts with which the first announcement of these facts was received have been entirely removed by careful examination of the locality by many scientists, both of France and England.

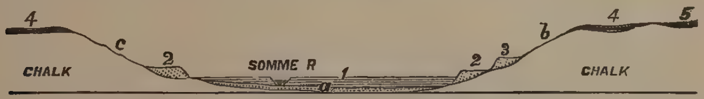

Fig. 990.—Section across Valley of the Somme: 1, peat, twenty to thirty feet thick, resting on gravel, *a*; 2, lower-level gravels, with elephant bones and flint implements, covered with river-loam twenty to forty feet thick; 3, upper level gravels, with similar fossils covered with loam, in all, thirty feet thick; 4, upland-loam, five to six feet thick; 5, Eocene-Tertiary.

The findings were in undisturbed gravels, both lower (2) and upper (3), beneath river-loam twenty to thirty feet thick. Supposing that the upper loam (4) represents the full Champlain flood-deposit, then 3 and 2 represent the later Champlain epoch.

In England, also, at Hoxne, similar flint implements, associated with bones of extinct animals, were found in strata *underlying the higher-level river-gravels, but overlying the bowlder-drift or true glacial deposit.* This fixes the age as Champlain. Still older than the high-level river-gravels are the *plateau* gravels of Kent, in which Prof. Prestwich finds extremely rude flints. These gravels seem to belong to the *earliest Glacial*, if not earlier still. The flints are probably the oldest *undoubted* relics of man yet found. Many other examples of similar findings might be cited.

b. **Bone-Caves—Engis Skull.**—In the caves of Belgium and Germany have been found human *bones* associated with extinct animals. The best example is that of the skull found in a cave at *Engis*, on the banks of the Meuse, near Liége. Of the great antiquity of this skull there seems to be no doubt. It was found in bone breccia, associated with bones of Quaternary *extinct* species and *living* species, *beneath a stalagmitic crust.* This association unmistakably indicates the middle or latter part of the Quaternary period.

Neanderthal Skull.—In a cave at Neanderthal, near Düsseldorf, was found a very remarkable human skeleton, which has greatly excited the interest of scientific men. The limb-bones are large, and the protuberances for muscular attachments very prominent; the skull very thick, very low in the arch, and very prominent in the brows. It has been supposed by some to be an intermediate form between man and the ape; but, according to the best authority, it is in no respect intermediate, but truly human. It is probably the skeleton of a man exceptionally muscular in body and low in intelligence. The evidences of antiquity are of the same kind, but less complete than in the case of the Engis skull, though it probably belongs to the same or, perhaps, even an earlier epoch. The Engis skull, on the other hand, is a *well-shaped average human skull.* A figure of the Engis skull is given herewith (Fig. 991), and a comparison in outline of the Neanderthal with the ape and European (Fig. 992).

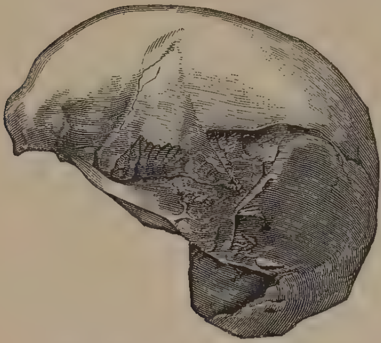

Fig. 991.—Engis Skull, reduced (after Lyell).

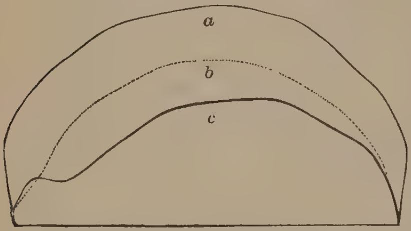

Fig. 992.—Comparison of Forms of Skulls: *a*, European; *b*, the Neanderthal man; *c*, a chimpanzee (after Lyell).

Recently there have been found in a cave at Spy, Belgium, two nearly complete skeletons, which seem to be of the same type as the Neanderthal man, and with the latter are supposed to belong to a distinct and very early race. They are believed to have been men of short stature, broad-shouldered, bowed thighs, slightly-bent knees, and semi-erect posture, but nevertheless distinctly human. The skeletons were found associated with the remains of all the characteristic Quaternary animals and implements of the rudest kind. Their age was either Champlain or interglacial.*

Mentone Skeleton.—Several years ago an almost perfect skeleton of a Palæolithic man was found in a cave at Mentone, near Nice. It is that of a tall, well-formed man, with average or more than average-sized skull, and a facial angle of 85°. The antiquity of this man is undoubted, for his bones are associated with those of the cave-lion, cave-bear, rhinoceros, reindeer, together with living species. The bones of the skeleton are all in place, surrounded with the implements of the chase (flint implements), and the spoils of the chase, viz., the bones of reindeer, *perforated* teeth of stag, etc. Of the latter, twenty-two lay about his head. These are supposed to have been worn as a chaplet. This Quaternary man seems to have laid himself down quietly in his cave-home and died, and Nature covered his grave with a tablet of stalagmite.*

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* Nature, vol. xxxv, p. 564, 1887.

All these, and many more which might be mentioned, belong to the *early Palæolithic*, although the last is probably a transition to the next or Reindeer age. They were contemporaneous with the mammoth, the rhinoceros, the hippopotamus, the cave-bear, the cave-lion, the cave-hyena, and other extinct animals; but the reindeer had not yet, to any extent, invaded Middle Europe from the north. They seem to have been savages of the lowest type, living by hunting and dwelling in caves, and their implements were of the rudest kind. There is no evidence of *agriculture* or of *domestic animals*. In many cases there have been found some anatomical characters of a low or animal type, such as *flattened shin-bones*, very *prominent occipital protuberance*, less than usual separation between the *temporal ridges*, large *size of the wisdom teeth*, and, in the case of the Neanderthal race, a very low arch of the skull, and bent knees, etc. But all these characters, unless we except the last two, are found now in some savage races, either as racial or as individual peculiarities. The earliest men yet found are in no sense connecting links between man and ape. They are distinctively human.

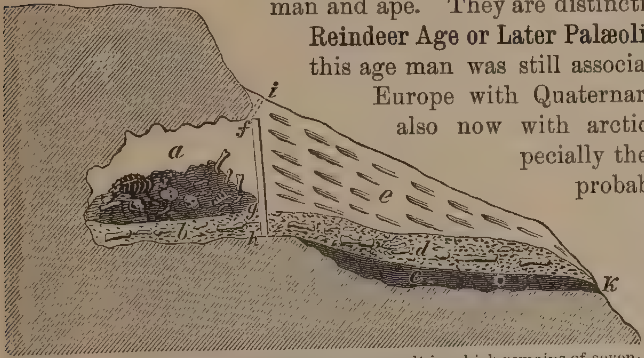

Fig. 993.—A Section of the Aurignac Cave: *a*, vault in which remains of seventeen human skeletons were found; *b*, made ground, two feet thick, in which human bones and entire bones of extinct and living mammals, and works of art, were imbedded; *c*, layer of ashes and charcoal, eight inches thick, with broken, burnt, and gnawed bones of extinct and living mammals, also hearth-stones and works of art; *d*, deposit with similar contents; *e*, talus washed down from hill above; *f g*, slab of stone which closed the vault; *f i*, rabbit-burrow, which led to discovery.

Reindeer Age or Later Palæolithic.—During this age man was still associated in Middle Europe with Quaternary animals, but also now with arctic animals, especially the reindeer. It probably corresponds with the Terrace or perhaps Second Glacial epoch. The implements were still chipped, but much more neatly.

Aurignac Cave.—This sepulchral cave and its rich contents were accidentally discovered by a French peasant. Fig. 993 is a diagram section of the cave, taken from Lyell.

On removing the talus, *e*, a slab of rock, *f g*, was exposed, covering the mouth of the cave, *a*. In this cave were found seventeen human skeletons of both sexes and of all sizes, together with entire bones of extinct animals and works of art. Outside of the cave was found a deposit, *c* and *d*, consisting of ashes and cinders, mingled with burnt and split and gnawed bones of recent and extinct animals, and works of art. The conclusion reached by M. Lartet is, that this was a family or tribal burial-place; that in the cave along with the bodies were placed funereal gifts in the form of trinkets and food; and that the funereal feast was cooked and eaten on the level space in front of the cave; and, finally, that carnivorous beasts gnawed the bones left on the spot. It is evident that the Aurignac men practiced religious rites which indicated a belief in immortality.

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* Recent findings throw some doubt on the Palæolithic age of the Mentone man. He may have been an early Neolithic man buried in Palæolithic ground. Several other skeletons have been recently found in the same locality.—Nature, vol. xlix, p. 42, 1893.

The following is a list of the animals the remains of which were found in and about the cave; those marked † are either wholly extinct or extinct in this locality:

FAUNA OF AURIGNAC CAVE.

CARNIVORES.		HERBIVORES.	
†Cave-bear	5 or 6	†Mammoth	2 molars.
Brown bear	1	†Rhinoceros	1
Badger	1 or 2	†Horse	12–15
Polecat	1	†Ass	1
†Cave-lion	1	Hog	1
Wild-cat	1	Stag	1
†Cave-hyena	5–6	†Irish elk	1
Wolf	3	Roebuck	3–4
Fox	18–20	†Reindeer	10–12
		†Aurochs	12–15

Perigord Caves.—In Southwestern France, along the course of the river Vézère, are found many caves in which are preserved interesting relics of man ranging from early to late Palæolithic. The Palæolithic Aquitanians seem to have been somewhat more advanced, and of a more

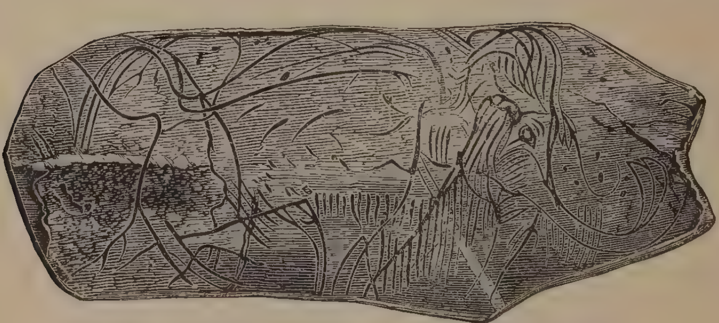

Fig. 994.—Drawing of a Mammoth by Contemporaneous Man.

peaceful temper, than the early Palæolithic men already described. Although there is no evidence of agriculture, they lived by *fishing* as well as by hunting. This is shown by the number of fishing-hooks of bone found there. They seemed also to have had a taste and some skill in drawing, for they have left some drawings of contemporaneous but now extinct animals, especially the mammoth, the reindeer, and the horse. Fig. 994 is a piece of reindeer-horn on which is a rude etching of the mammoth.

Conclusions.—It seems evident that *in Europe* the earliest men were contemporaneous with a large number of now extinct animals, and were a principal agent in their extinction; that they saw the flooded rivers of the Champlain epoch, and the great glaciers of the Second Glacial epoch; but there is no reliable evidence yet of their existence before the *First Glacial* epoch.

Neolithic Man; Refuse-Heaps; Shell-Mounds; Kitchen-Middens.

In Northern Europe, especially in Denmark, are found shell-mounds of great size, 1,000 feet long, 200 feet wide, and ten feet high. They are probably the accumulated refuse of annual tribal feasts. The early races of men in all countries seem to have had the custom of gathering in large numbers at stated intervals, and feasting on shell-fish and other animals, and leaving their remains in large heaps to mark the spot of assembly. The evidences of a very marked advance are found in these heaps. The implements are many of them carefully shaped or else polished by rubbing. There are no longer any remains of extinct animals, but only of living animals; and there are now found remains of at least one domestic animal, viz., the dog, though not yet any evidence of agriculture. We have evidence also at this time of organized communities.

Transition to the Bronze Age—Lake-Dwellings.—In the Swiss, Austrian, and Hungarian lakes are found abundant evidences of a more advanced race than any yet mentioned, which had the singular custom of dwelling in houses constructed on piles in the lakes, and connected with the land by means of piers or bridges. Similar lake-dwellings are found *now* in New Guinea and in South America, and very recently, by Lieutenant Cameron, in Africa.* By means of dredging, a great number and variety of implements of polished stone and of bronze have been obtained. Some of these were evidently used for ornament, some for domestic purposes, some for agriculture; some were weapons of war, some fishing-tackle. Many of these are wrought with great skill and taste. *Domestic animals*—ox, sheep, goat, and dog; *cereal grains*—wheat and barley; *fruits*—wild apples, blackberry, etc.; coarse cloth, not woven but plaited—have also been found. In a word, we have here all the evidences of communities far above the state of savagism.

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* Nature, vol. xiii, p. 202, January, 1876.

From this time the history of man may be traced, by means of his remains, through the time of Megalithic structures, through the Roman age, step by step, to the present time. But this belongs to the archæologist, not the geologist. The Neolithic may be regarded as the beginning of the Psychozoic era—the connecting link between geology and archæology. The Bronze age and all that follows it belong clearly to archæology.

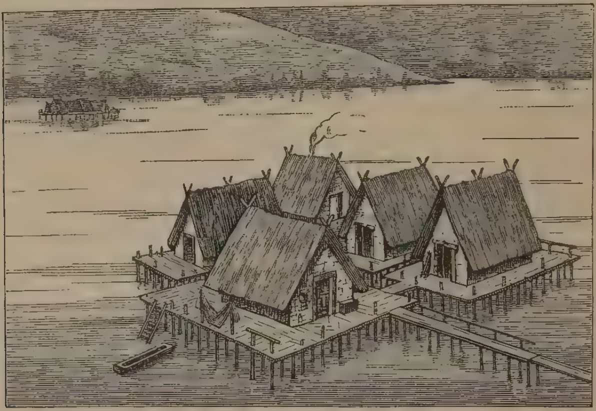

FIG. 995.—Lake-Dwellings, restored (after Mortillet).

Primeval Man in America.

Supposed Pliocene Man—Calaveras Skull.—Several cases are reported of human bones and works of art having been found in the sub-lava drift described on page 627. These cases are none of them thoroughly well attested, though the evidence is such as to make us suspend our judgment. The best attested cases are the Calaveras skull mentioned by Whitney, and the Table Mountain skull reported by C. F. Winslow. Besides these there are several cases reported of mortars and pestles found in the sub-lava deposit. Many claim these as evidence of the existence of man in a somewhat advanced stage of progress (at least as much so as the Neolithic man of Europe), on the Pacific coast, during the Pliocene period. The doubts in regard to this extreme antiquity of man are of four kinds, viz.: 1. Doubts as to the Pliocene age of the gravels—they may be early Quaternary. 2. Doubts as to the authenticity of the finds, no scientist having seen any of them *in situ*. 3. Doubts as to the undisturbed condition of the gravels, for auriferous gravels are especially liable to disturbance, and therefore may have been disturbed by native races before the arrival of the white man. 4. The character of the implements said to have been found gives peculiar emphasis to this last doubt, *for they are not Palæolithic*, but *Neolithic*.

In any case, and whatever be the geological age of the sub-lava drift, if man should be undoubtedly found there, it would show an immense antiquity; for, since the lava-flow, cañons have been cut by the present rivers 2,000 or 3,000 feet deep in solid slate-rock.

Carson Footprints.—In 1882 scientific attention was first drawn to certain remarkable tracks, resembling those of gigantic men, in the sandstone-quarry near Carson, Nevada. The floor of the quarry (which constitutes the yard of the State Prison) is a level area of about two acres. The whole surface of this area is covered with the tracks of many kinds of animals. The depth of the tracks shows that the material was soft mud at the time the tracks were made. The most remarkable are undoubted tracks of elephants (mammoth) and especially certain strangely man-like tracks of enormous size. These were eighteen to twenty inches long and eight inches wide. The stride was about a yard, and the distance between right and left series was nineteen inches.

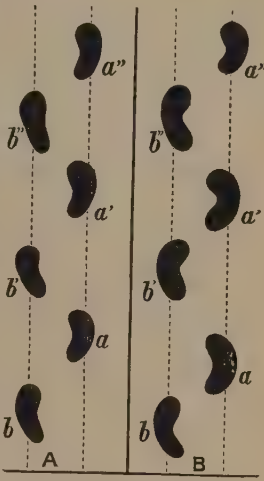

FIG. 996.—Two Series of Tracks in Carson Prison-yard.

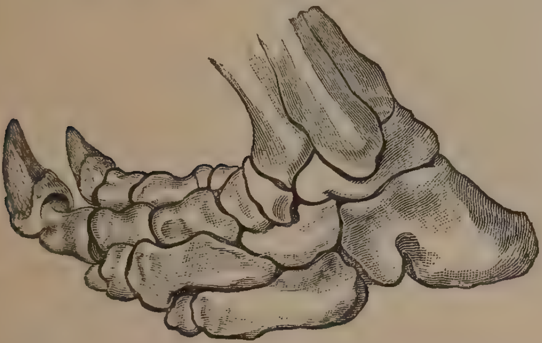

FIG. 997.—Left hind-foot of Mylodon robustus, × ⅙ (after Owen).

There has been much discussion as to the nature of these tracks. Some think that they are human, and account for their great size by supposing that the men wore large sandals. Others think that they are the tracks of a large ground-sloth such as the mylodon, which is known to have lived on the Pacific coast in Quaternary times.* Both in size and shape they are certainly much like the hind-foot of the mylodon (Fig. 997). But if made by a quadruped, the larger hind-foot must have obliterated the impression of the fore-foot, for there are apparently but two series of tracks; and the feet must have been clogged with mud, for no impression of toes is seen. It is significant, however, that the elephant-tracks, also, formed but two series.

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* Am. Journ. Sci., vol. xxvi, p. 139, Aug., 1883.

The weight of evidence is probably in favor of the mylodon, but in any case there seems no reason to believe the age of the strata to be earlier than the Quaternary. The only reason for assigning them to an earlier period (Pliocene) is their lithified condition. But the presence in the quarry of hot springs, containing abundance of lime-carbonate, sufficiently accounts for this.

Quaternary Man.—Leaving out all doubtful cases, the first appearance of man in America seems to have been about the same time as or, perhaps, a little later than in Europe. On the Pacific coast his implements are found in great abundance in river-gravels, associated with remains of the mammoth, the great mastodon, and the horse. On the eastern part of the continent, also, the existence of man before the ice-sheet had disappeared from the United States, is almost certain. A good example of this is found in the discovery by Miss Babbitt, at Little Falls, Minnesota, of rude flint implements in deposits, which were formed during the final retreat of the ice-sheet from that region.* Another good example is the discovery by Abbott, in gravels near Trenton, New Jersey, of rude flint implements, similar to Palæolithic implements everywhere. The gravels are acknowledged to have been formed during the retreat of the ice-sheet from New Jersey. We give here a figure of one of these flints (Fig. 998). Still more recently human implements have been found in Ohio, under conditions which seem to prove that man lived there while the northern part of the Mississippi Valley was *still ice-sheeted* (Wright). And still more recently, (1895) another finding of a rude flint in un-

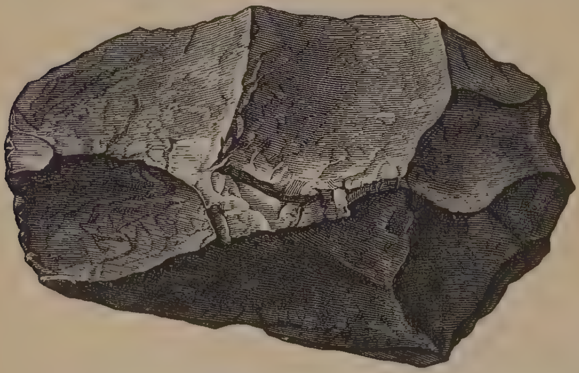

FIG. 998.—Palæolith found by Abbott in New Jersey, slightly reduced (after Wright).

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* American Naturalist, vol. xviii, pp. 594, 697, 1884; and Wright's Ice Age, p. 538 *et seq.*

disturbed glacial gravel, near Steubenville, Ohio, leaves little doubt that man lived in Ohio during the retreat of the ice-sheet. It must be said, however, that doubt has been cast on all these cases by competent observers.

There seems to be little doubt, therefore, that in America, as in Europe, man saw the retreating ice-sheet and the flooded lakes and rivers of the Champlain times.

The history of the American man can be traced onward in refuse-heaps and shell-mounds; in the great mounds of the so-called mound-builders, scattered over the whole Eastern part of the continent, but especially abundant in the valley of the Mississippi; and, finally, in the wonderful cliff-dwellings and buried cities of New Mexico and Arizona. But all this, though of extreme interest, belongs to archæology rather than geology.

Quaternary Man in Other Countries.—In *India*,* Palæolithic implements, precisely like those found in Europe and elsewhere, were found, in 1873, associated with extinct species of elephant, hippopotamus, rhinoceros, and bear, in Quaternary deposits. In the South American bone-caverns human remains have been found associated with Quaternary animals.

Very recently (1895) there comes the news of the finding in Java, in deposits of earliest Quaternary or late Pliocene age, of a supposed veritable *missing link*—i. e., of an anthropoid, more man-like than any yet known. It has been made by its finder—Du Bois—into a new genus

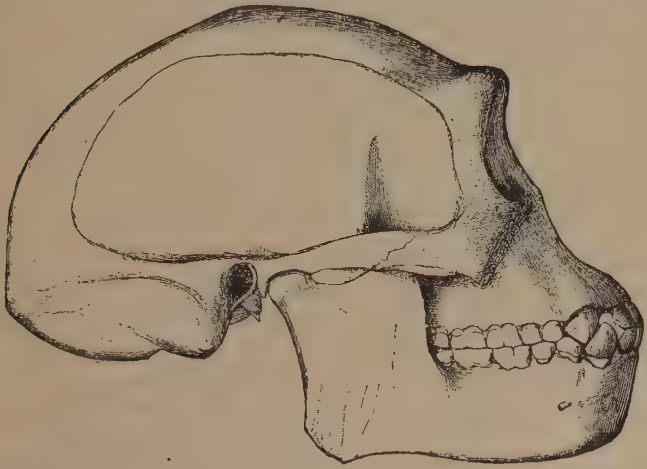

FIG. 999.—Restoration of the Skull of Pithecanthropus erectus, × $\frac{2}{5}$ (after Du Bois).

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* American Journal of Science, 1875, vol. x, p. 232.

and called *Pithecanthropus* (man-ape) *erectus*. The skull and the teeth of this creature are far lower and more ape-like than those of any supposed man yet found, but the thigh-bone shows undoubted

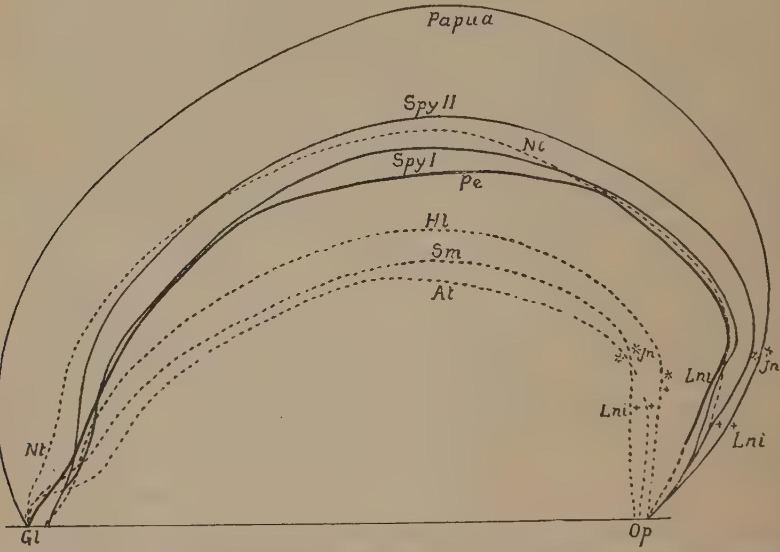

FIG. 1000.—Profile outlines of the Skull of Pithecanthropus (*Pe*) compared with those of a Papuan man, the man of Spy, Neanderthal man (*Nt*), Hylobates (*Hl*), Semnopithecus (*Sm*), and Anthropopithecus (*At*) (from a figure by Du Bois, modified by Marsh).

erect attitude. Judging from the skull and teeth it is certainly intermediate between ape and man, but on which side of the dividing line it should be assigned is still doubtful. In Fig. 999 we give a restoration of the skull of this animal, and in Fig. 1000 outlines of the vault of the skulls of modern man, Palæolithic man, *Pithecanthropus*, and several apes.

Man, therefore, has been traced back with certainty to the Champlain and even to the interglacial epoch. It is possible that he may be hereafter traced farther to the Glacial or pre-Glacial period. Some confidently expect that he will be traced to the Miocene, but this seems extremely improbable, for the following reasons:

a. He has been diligently searched for, without success. Now, while negative evidence is rightly regarded as of little value in geology, yet, in this instance, it is undoubtedly of far more than usual value, because man's *works* are far more numerous and far more imperishable than his *bones*.

b. Man probably came in with the present mammalian fauna. We repeat here the diagram illustrating the law of extinction and appearance of species (Fig. 1001). It is seen that lower species are far less rapidly changed than higher. Living foraminifers may be traced back into the Cretaceous; living shells and other invertebrates to the beginning of the Tertiary: but living mammals pass out rapidly and disappear in the Middle Quaternary. Not a single species of mammal now living is found in the Tertiary. Shall man, the highest of all, be the only exception? Man is one of the present mammalian fauna, and came in with it.

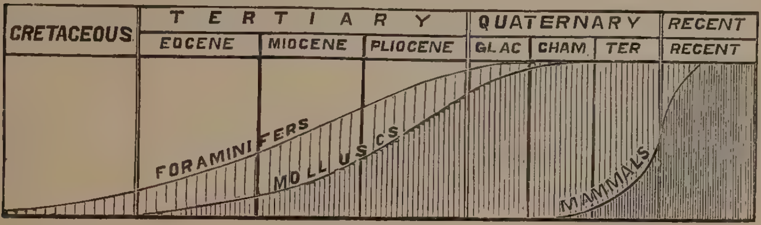

FIG. 1001.

c. But, again, many distinct mammalian faunas have appeared and disappeared since the beginning of the Miocene. The Miocene mammalian fauna is totally different from the Eocene; the Pliocene totally different from the Miocene; the Quaternary from the Pliocene; and the present from the Quaternary. This is graphically represented in the diagram, Fig. 1002, in which the alternate shaded and white spaces represent five consecutive mammalian faunas (there are really many more than five) overlapping each other, but substantially distinct. It seems in the highest degree improbable that man, a mammal, should survive the appearance and disappearance of several mammalian faunas.

Or, again, to put it still another way: We have seen (p. 561, Fig. 935) that, speaking generally, existing mammalian *species* commenced to be introduced in the Quaternary; existing *genera* in the Pliocene; and existing *families* in the Miocene. If, therefore, a tool-making animal should be found in the Miocene, as some believe, it might be of the family of *Hominidæ*, but not the genus *homo*. If such should be found in the Pliocene, it might be of the genus *homo*, but not the species *sapiens*. Even the earliest Quaternary man—the so-called Neanderthal race—is supposed by Mortillet to have been a different species from existing man.

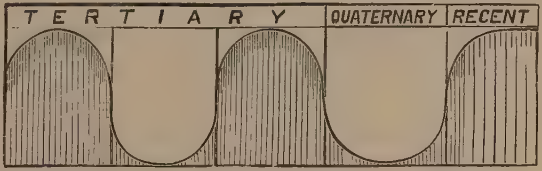

FIG. 1002.—Diagram illustrating the Appearance and Extinction of Successive Mammalian Faunæ.

Time since man appeared.—Geology reckons her time in periods, epochs, etc.; History hers in years. It is impossible to express the one chronology in terms of the other except in a very rough approximative way, for want of a reliable common measure. If Mr. Croll's theory of glacial cold should indeed prove true, then we might hope to measure man's time on the earth with some degree of accuracy. But in the absence of confidence in this theory, our only resource is to use the measure which we have already used on several occasions, viz., the effects of causes now in operation. This measure, however, can give but very rough approximate results.

There is no doubt that very great changes, both in physical geography and in the mammalian fauna, have taken place since man appeared. Judging by the rate of changes still in progress, we are naturally led to a conviction of a lapse of time very great in comparison with that recorded in history. On the other hand, some attempts to estimate more accurately by means of the growth of deltas in which have been found implements of the Roman age, the Bronze age, and the Stone age; and by the progressive erosion of lake-shores and the recession of waterfalls, which is supposed to have commenced after the Champlain epoch, have led to very moderate results, viz., 7,000 to 10,000 years. While these results can not be received with any confidence, yet it is hoped that many such will continue to be made.

In conclusion, we may say that we have as yet no certain knowledge of man's time on the earth, unless we adopt Croll's theory of the Glacial climate. It may be 100,000 years, or it may be only 10,000 years.

II.—Character of Primeval Man.

In regard to the second question, viz., the character of primeval man, we will make but one remark. We have seen that the earliest men yet discovered in Europe or America, though low in the scale of civilization, were distinctively human, and not in any sense an intermediate link between man and the ape. Nevertheless, we must not forget that the cradle of mankind was probably in Asia. Man came to Europe and America by migration. The intermediate link, if there be any such, must be looked for in Asia, and more probably in southern Asia; and there, indeed, such a link is supposed to have been found in *Pithecanthropus*. This question can only be settled by a complete knowledge of the Quaternary of that country.

In any case, man is the ruler only of the Psychozoic era. The presence of man in Quaternary times must be regarded as an example under the *law of anticipation* (p. 291). He only fairly *established* his supremacy in the Recent epoch, and therefore the age of man and the Psychozoic era ought to date from that time.

LIST OF THE PRINCIPAL AUTHORITIES FOR THE ILLUSTRATIONS IN THIS WORK, AND THE BOOKS FROM WHICH THEY HAVE BEEN TAKEN.

AGASSIZ, L. Études sur les Glaciers; Poissons Fossiles.

ASHBURNER, CHARLES A. Anthracite Fields of Pa.

AUTHOR. American Journal of Science, III, 1872–'89; also many (about 150) diagrammatic illustrations throughout this work.

BAILEY, J. W. Am. Jour. of Sci., II, i.

BEECHER. Am. Jour. of Sci., 1889.

BRADLEY, F. H. Geological Chart of the U. S.

BROGNIART, A. Histoire des Végétaux Fossiles.

BUCKLAND, W. Bridgewater Treatise.

CHAMBERLIN, T. C. Kettle Moraine. Trans. Wis. Acad. Sci., 1879.

CONRAD, T. A. Jour. Acad. Sci., Philadelphia.

COPE, E. D. Hayden's U. S. Geog. and Geol. Survey, vol. ii—Cretaceous Vertebrates; Newberry's Ohio Survey Pal.—Reptiles of the Coal; Proc. Am. Phil. Soc., vols. xvii and xix—Permian and Jurassic Reptiles; Origin of the Fittest.

DADDOW, S. H. Coal, Iron, and Oil.

DANA, J. D. Wilkes's U. S. Explor. Exped.—vol. on Geology; Manual of Geology.

DAVIS, W. M. Trias of Conn. River. Am. Jour. of Sci., 1889.

DAWSON, J. W. Acadian Geology.

DE LA BECHE, H. Geological Observer—Sections and Views of Geological Phenomena.

DE LA NÖE and DE MARGERIE. Les Formes du Terrain.

DE MARGERIE and HEIM. Dislocation de l'Écorce Terrestre.

D'ORBIGNY, A. Paléontologie et Géologie.

EMMONS, E. Rep. Geol. of N. Y.; Rep. Geol. of N. C.

EWING. Seismograph.

FAVRE, Prof. ALPH. Archives des Sciences, vol. lxii.

FONTAINE, W. M. Flora of Potomac Formation, U. S. Geol. Survey. Monograph.

FORBES, J. Alps of Savoy.

FOSTER and WHITNEY. Rep. on Geology of L. Superior District.

FRITSCH. Permian Fauna.

Gabb, W. M. Whitney's Geol. Survey of California.

Gaudry, A. Monde Animale.

Geikie, A. Text-Book of Geology.

Geikie, J. Great Ice Age.

Gilbert, G. K. Geology of the Henry Mountains.

Gratacap. Concretions or Nodules. Am. Nat., 1884.

Günther, A. Trans. Roy. Soc., 1871.

Guyot, A. Physical Geography.

Hall, J. Rep. Palæontology of N. Y.; Rep. Geol. of Iowa; Rep. on State Cabinet of N. Y.

Hayden, F. V. Rep. Geog. and Geol. Survey of Territories, 1871–'73.

Heer, Prof. Primeval World of Switzerland.

Hilgard, E. W. Rep. Agric. and Geol. of Miss., 1860.

Hitchcock, C. H. Geol. Map of U. S.

Hitchcock, E. Ichnology of Mass., 1858.

Holmes, W. H. Drawing of Geyser Eruption.

Howell, E. E. U. S. Geog. Survey by Wheeler, vol. iii—Geology.

Jukes and Geikie. Manual of Geology.

Huxley, T. H. Manual of Anat. of Vertebrates; Anat. of Invertebrates; Rhynchosaurs. Quar. Jour. Geol. Soc., 1887.

Jackson, W. H. Photograph of Geyser Eruption.

Johnstone, A. K. Phys. Atlas, last edition.

King, Clarence. Geol. Survey of 40th Parallel, vol. i.

Leidy, J. Cretaceous Reptiles of U. S.; Smithsonian Contributions, 1865; Fossil Vertebrates of U. S.; Hayden's Geol. Survey of Terr., vol. i.

Lesley, J. P. Manual of Coal and its Topography.

Lesquereux, L. Owen's Rep. Geol. of Ky.; Owen's Rep. Geol. Ark.; Hayden's Geog. and Geol. Survey, vol. vi; Cret. Flora of U. S.

Logan, W. Rep. Geol. Canada.

Lyell, C. Principles of Geology; Elements of Geology; Antiquity of Man.

Mallet, F. R. Barren Island. Geol. Survey of India.

Mantell, G. A. Fossils of British Museum.

Mâout and Decaisne. General System of Botany.

Marsh, O. C. Jurassic and Cretaceous Reptiles and Birds, and Jurassic and Tertiary Mammals; Am. Jour. of Sci., 1871–'90.

Meek and Worthen. Geol. Survey of Ill., vols. ii, iii, iv, v, vi.

Meek, F. B. Whitney's Geol. Survey of California, vol. i; Newberry's Geol. Survey of Ohio Pal., vols. i and ii; Palæontology of Upper Missouri; Smithsonian Contributions, 1864.

Murchison, R. I. Siluria.

Newberry, J. S. Rep. Geol. Survey of Ohio; Geol. of Macomb Expedition; Pacific R. R. Reports, vol. vi.

Nicholson, H. A. Manual of Palæontology; Manual of Zoölogy; Ancient Life History.

Osborn, H. F. Mesozoic Mammals; Jour. Acad. Nat. Sci., Philadelphia, 1888; Mammalia of Uintah Formation. Mem. Am. Phil. Soc., 1889.

Owen, D. D. Rep. Geol. of Wisconsin, Iowa, etc.

Owen, R. British Fossil Mammals; Palæontology; Trias Reptiles; Quar. Jour. Geol. Soc., 1887.

Packard, A. S. Life-Histories; Manual of Zoölogy; Syncarida. Mem. Jour. Nat. Acad. Sci.

Phillips, J. Manual of Geology; Geology of Oxford.

Pictet, F. J. Traité de Paléontologie.

Powell, J. W. Exploration of Colorado River; Geology of Uintah Mountains.

Prestwich. Geology.

Rogers, H. D. Rep. Geol. of Pennsylvania.

Russell, I. C. Lake Lahontan; Southeastern Oregon. U. S. G. S. Monograph, 11. Annual Report, 1884.

Safford, J. M. Rep. Geol. of Tennessee.

Seeley, H. G. Geol. Mag., vol. viii, 1881.

Scudder, S. H. Worthen's Rep. Geol. of Ill., vol. iii. Eighth Annual Report U. S. G. S.

Sekiya, S. Seism. Soc. of Japan, vol. xi.

Sharpe, D. Quar. Jour. Geol. Soc., vol. iii, 1847.

Sorby, H. C. Philosophical Magazine, 2d series, vol. xi.

Stevenson, J. J. Wheeler's U. S. Geol. Survey, vol. iii—Geology.

Taylor, R. C. Statistics of Coal.

Traquair. Devonian Fishes. Ann. and Mag. Nat. Hist., 1890.

Tyndall, J. Glaciers of the Alps.

Upham, Warren. Ice Sheet Moraine; Geol. Survey of Minn., 1880.

Wailes, B. L. C. Rep. Agric. and Geol. of Miss., 1854.

Walcott, C. D. Rep. N. Y. Cabinet of Nat. Hist., 1877.

Wallace, A. R. Geographical Distribution of Animals; Island Life.

Ward, H. Illustrated Catalogue of Casts.

Ward, Lester F. Laramie Flora; U. S. G. S. Bulletin, 37.

Wheeler, G. M. U. S. Geog. Survey west of 100th Meridian.

White, C. A. Wheeler's Survey, vol. iv—Palæontology. U. S. G. S. Annual Report.

Whitney, J. D. Geol. Survey of California; Geol. of L. Superior District; Auriferous Gravels of California.

Woodward, S. P. Manual of Mollusca.

Worthen. Geol. Survey of Illinois.

Zittell. Traité de Paléontologie.

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